Approximate Model Counting

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March 23, 2024

Abstract

Approximate model counting is the task of approximating the number of solutions to an input formula. This entry formalizes ApproxMC, an algorithm due to Chakraborty et al. [1] with a probably approximately correct (PAC) guarantee, i.e., ApproxMC returns a multiplicative $(1+\varepsilon)$-factor approximation of the model count with probability at least $1-\delta$, where $\varepsilon > 0$ and $0 < \delta \leq 1$. The algorithmic specification is further refined to a verified certificate checker that can be used to validate the results of untrusted ApproxMC implementations (assuming access to trusted randomness).

Contents

1 Preliminary probability/UHF lemmas

This section proves some simplified/specialized forms of lemmas that will be used in the algorithm's analysis later.

theory *ApproxMCPreliminaries* **imports**
Frequency-Moments.Probability-Ext
Concentration-Inequalities.Paley-Zygmund-Inequality
begin

lemma *card-inter-sum-indicat-real*:
assumes *finite A*
shows *card* $(A \cap B)$ = *sum* (*indicat-real B*) *A*
by (*simp add*: *assms indicator-def*)

lemma *card-dom-ran*:
assumes *finite D*
shows *card* $\{w.\ dom\ w = D \wedge ran\ w \subseteq R\}$ = *card R* ^ *card D*
using *assms*
proof (*induct rule*: *finite-induct*)
case *empty*
have $\{w::'a \Rightarrow 'b\ option.\ w = Map.empty \wedge ran\ w \subseteq R\} = \{Map.empty\}$
by *auto*
then show *?case*
by *auto*
next
case (*insert a A*)
have *1*: *inj-on* $(\lambda(w,\ r).\ w(a \mapsto r))$
$(\{w.\ dom\ w = A \wedge ran\ w \subseteq R\} \times R)$
unfolding *inj-on-def*
by (*smt* (*verit*, *del-insts*) *CollectD SigmaE fun-upd-None-if-notin-dom local.insert*(*2*) *map-upd-eqD1 prod.simps*(*2*) *restrict-complement-singleton-eq restrict-upd-same*)
have *21*: $(\lambda(w,\ r).\ w(a \mapsto r))$ ‘
$(\{w.\ dom\ w = A \wedge ran\ w \subseteq R\} \times R) \subseteq$
$\{w.\ dom\ w = insert\ a\ A \wedge ran\ w \subseteq R\}$
unfolding *image-def*
using *CollectD local.insert*(*2*) **by** *force*

have $\bigwedge x.\ dom\ x = insert\ a\ A \Longrightarrow$
$ran\ x \subseteq R \Longrightarrow$
$\exists\, xa.\ dom\ xa = A \wedge$
$ran\ xa \subseteq R \wedge (\exists\, y{\in}R.\ x = xa(a \mapsto y))$
by (*smt* (*verit*, *del-insts*) *Diff-insert-absorb domD dom-fun-upd fun-upd-triv fun-upd-upd insert.hyps*(*2*) *insertCI insert-subset ran-map-upd*)
then have *22*:
$\{w.\ dom\ w = insert\ a\ A \wedge ran\ w \subseteq R\} \subseteq$
$(\lambda(w,\ r).\ w(a \mapsto r))$ ‘
$(\{w.\ dom\ w = A \wedge ran\ w \subseteq R\} \times R)$

by (*clarsimp simp add*: *image-def*)

have *bij-betw* (λ(*w*,*r*). *w*(*a*↦*r*))
({*w*. *dom w* = *A* ∧ *ran w* ⊆ *R*} × *R*)
{*w*. *dom w* = *insert a A* ∧ *ran w* ⊆ *R*}
unfolding *bij-betw-def*
using *1 21 22* **by** *clarsimp*

then have *card* {*w*. *dom w* = *insert a A* ∧ *ran w* ⊆ *R*} = *card* ({*w*. *dom w* = *A* ∧ *ran w* ⊆ *R*} × *R*)
by (*auto simp add*: *bij-betw-same-card 1 21 22*)

moreover have ... = *card R* ^ *card A* ∗ *card R*
by(*subst card-cartesian-product*) (*use insert.hyps*(*3*) **in** *auto*)

ultimately show *?case*
using *insert.hyps* **by** (*auto simp add*: *card-insert-if*)
qed

lemma *finite-set-pmf-expectation-sum*:
fixes *f* :: *'a* ⇒ *'c* ⇒ *'b*::{*banach*, *second-countable-topology*}
assumes *finite* (*set-pmf A*)
shows *measure-pmf.expectation A* (λ*x*. *sum* (*f x*) *T*) =
(∑ *i*∈*T*. *measure-pmf.expectation A* (λ*x*. *f x i*))
apply (*intro Bochner-Integration.integral-sum integrable-measure-pmf-finite*)
using *assms* **by** *auto*

lemma (**in** *prob-space*) *k-universal-prob-unif*:
assumes *k-universal k H D R*
assumes *w* ∈ *D α* ∈ *R*
shows *prob* {*s* ∈ *space M*. *H w s* = *α*} = *1* / *card R*
proof −
have *uniform-on* (*H w*) *R*
using *assms* **unfolding** *k-universal-def*
by *auto*

from *uniform-onD*[*OF this*]
have *prob*
{*ω* ∈ *space M*. *H w ω* ∈ {*α*}} =
real (*card* (*R* ∩ {*α*})) / *real* (*card R*) **.**

thus *?thesis*
using *assms* **by** *auto*
qed

lemma *k-universal-expectation-eq*:
assumes *p*: *finite* (*set-pmf p*)
assumes *ind*: *prob-space.k-universal p k H D R*

assumes S: *finite* S $S \subseteq D$
assumes a: $\alpha \in R$
shows
prob-space.expectation p
$(\lambda s.\ real\ (card\ (S \cap \{w.\ H\ w\ s = \alpha\}))) =$
real $(card\ S)$ / $card\ R$
proof −
have *1*: *prob-space* $(measure\text{-}pmf\ p)$
by (*simp add*: *prob-space-measure-pmf*)
have *2*: *space* $(measure\text{-}pmf\ p) = UNIV$ **by** *auto*
from *prob-space.k-universal-prob-unif*[*OF 1 ind - a*]
have $*$: $\bigwedge w.\ w \in S \Longrightarrow$
prob-space.prob $p\ \{s.\ H\ w\ s = \alpha\} = 1$ / *real* $(card\ R)$
using *S*(*2*) **by** *auto*

have *measure-pmf.expectation* p
$(\lambda s.\ real\ (card\ (S \cap \{w.\ H\ w\ s = \alpha\}))) =$
measure-pmf.expectation p
$(\lambda s.\ sum\ (indicat\text{-}real\ \{w.\ H\ w\ s = \alpha\})\ S)$
unfolding *card-inter-sum-indicat-real*[*OF S*(*1*)]
by *presburger*

moreover have ... =
$(\sum i \in S.$
measure-pmf.expectation p
$(indicat\text{-}real\ \{s.\ H\ i\ s = \alpha\}))$
apply (*subst finite-set-pmf-expectation-sum*)
using *assms* **unfolding** *indicator-def* **by** *auto*

moreover have ... =
$(\sum i \in S.$
measure-pmf.prob $p\ \{s.\ H\ i\ s = \alpha\})$
by *auto*

moreover have ... = $(\sum i \in S.\ 1$ / $card\ R)$
using $*$ **by** *auto*

ultimately show *?thesis* **by** *auto*
qed

lemma (**in** *prob-space*) *two-universal-indep-var*:
assumes *k-universal 2 H D R*
assumes $w \in D\ w' \in D\ w \neq w'$
shows *indep-var*
borel
$(\lambda x.\ indicat\text{-}real\ \{w.\ H\ w\ x = \alpha\}\ w)$
borel
$(\lambda x.\ indicat\text{-}real\ \{w.\ H\ w\ x = \alpha\}\ w')$
proof −

have Y: $(\lambda z.\ (\textit{of-bool}\ (z = \alpha))::\textit{real}) \in (\textit{count-space}\ \textit{UNIV}) \rightarrow_M \textit{borel}$
by *auto*

have *k-wise-indep-vars 2*
(λ-. *count-space UNIV*)
H D
using *assms*
unfolding *k-universal-def*
by *auto*

then have *indep-vars* (λ-. *count-space UNIV*) *H* $\{w, w'\}$
unfolding *k-wise-indep-vars-def*
by (*metis UNIV-bool assms(2) assms(3) card.empty card.insert card-UNIV-bool card-insert-le empty-iff empty-subsetI finite.emptyI finite.insertI insert-subset order.refl singletonD singleton-insert-inj-eq'*)

from *indep-var-from-indep-vars*[*OF assms(4) this*]
have *indep-var*
(*count-space UNIV*) (*H w*)
(*count-space UNIV*) (*H w'*) **.**

from *indep-var-compose*[*OF this Y Y*]
show *?thesis*
unfolding *indicator-def*
by (*auto simp add*: *o-def*)
qed

lemma *two-universal-variance-bound*:
assumes *p*: *finite* (*set-pmf p*)
assumes *ind*: *prob-space.k-universal* (*measure-pmf p*) *2 H D R*
assumes *S*: *finite S S* $\subseteq$ *D*
assumes *a*: $\alpha \in R$
shows
measure-pmf.variance p
($\lambda s.$ *real* (*card* ($S \cap \{w.\ H\ w\ s = \alpha\}$))) $\leq$
measure-pmf.expectation p
($\lambda s.$ *real* (*card* ($S \cap \{w.\ H\ w\ s = \alpha\}$)))
proof −
have *vb*: *measure-pmf.variance p*
($\lambda x.$ (*indicat-real* $\{w.\ H\ w\ x = \alpha\}$ *i*)) $\leq$
measure-pmf.expectation p
($\lambda x.$ (*indicat-real* $\{w.\ H\ w\ x = \alpha\}$ *i*)) **for** *i*
proof −
have *measure-pmf.variance p*
($\lambda x.$ (*indicat-real* $\{w.\ H\ w\ x = \alpha\}$ *i*)) =
measure-pmf.expectation p
($\lambda x.$ (*indicat-real* $\{w.\ H\ w\ x = \alpha\}$ *i*)^2) −

```
    (measure-pmf.expectation p
      (λx. indicat-real {w. H w x = α} i))²
      apply (subst measure-pmf.variance-eq)
      by (auto simp add: p integrable-measure-pmf-finite)
    moreover have ... ≤ measure-pmf.expectation p
     (λx. (indicat-real {w. H w x = α} i)²)
      by simp
    moreover have ... = measure-pmf.expectation p
     (λx. (indicat-real {w. H w x = α} i))
    by (metis (mono-tags, lifting) indicator-simps(1) indicator-simps(2)
power2-eq-1-iff zero-eq-power2)
    ultimately show ?thesis by linarith
  qed

  have measure-pmf.variance p
    (λs. real (card (S ∩ {w. H w s = α}))) =
    measure-pmf.variance p
    (λs. sum (indicat-real {w. H w s = α}) S)
    unfolding card-inter-sum-indicat-real[OF S(1)]
    by presburger

  then have ... = (∑ i∈S.
       measure-pmf.variance p
        (λx. (indicat-real {w. H w x = α} i)))
    apply (subst measure-pmf.var-sum-pairwise-indep)
    using S prob-space-measure-pmf
    by (auto intro!: prob-space.two-universal-indep-var[OF - ind] simp
add: p integrable-measure-pmf-finite)

  moreover have ... ≤ (∑ i∈S.
       measure-pmf.expectation p
        (λx. (indicat-real {w. H w x = α} i)))
    by (simp add: sum-mono vb)
  moreover have ... = measure-pmf.expectation p
    (λs. sum (indicat-real {w. H w s = α}) S)
    apply (subst finite-set-pmf-expectation-sum)
    using assms by auto
  ultimately show ?thesis
    by (simp add: assms(3) card-inter-sum-indicat-real)
qed

lemma (in prob-space) k-universal-mono:
  assumes k' ≤ k
  assumesk-universal k H D R
  showsk-universal k' H D R
  using assms
  unfolding k-universal-def k-wise-indep-vars-def
  by auto
```

lemma *finite-set-pmf-expectation-add*:
assumes *finite* (*set-pmf S*)
shows *measure-pmf.expectation S* (λ*x*. ((*f x*)::*real*) + *g x*) =
measure-pmf.expectation S f + *measure-pmf.expectation S g*
by (*auto intro*: *Bochner-Integration.integral-add simp add*: *assms integrable-measure-pmf-finite*)

lemma *finite-set-pmf-expectation-add-const*:
assumes *finite* (*set-pmf S*)
shows *measure-pmf.expectation S* (λ*x*. ((*f x*)::*real*) + *g*) =
measure-pmf.expectation S f + *g*
proof −
have *g* = *measure-pmf.expectation S* (λ*x*. *g*)
by *simp*
thus *?thesis*
by (*simp add*: *assms finite-set-pmf-expectation-add*)
qed

lemma *finite-set-pmf-expectation-diff*:
assumes *finite* (*set-pmf S*)
shows *measure-pmf.expectation S* (λ*x*. ((*f x*)::*real*) − *g x*) =
measure-pmf.expectation S f − *measure-pmf.expectation S g*
by (*auto intro*: *Bochner-Integration.integral-diff simp add*: *assms integrable-measure-pmf-finite*)

lemma *spec-paley-zygmund-inequality*:
assumes *fin*: *finite* (*set-pmf p*)
assumes *Zpos*: ⋀*z*. *Z z* ≥ *0*
assumes *t*: ϑ ≤ *1*
shows
(*measure-pmf.variance p Z* + (*1*−ϑ)^*2* ∗ (*measure-pmf.expectation p Z*)^*2*) ∗
measure-pmf.prob p {*z*. *Z z* > ϑ ∗ *measure-pmf.expectation p Z*}
≥
(*1*−ϑ)^*2* ∗ (*measure-pmf.expectation p Z*)^*2*
proof −
have *prob-space* (*measure-pmf p*) **by** (*auto simp add*: *prob-space-measure-pmf*)

from *prob-space.paley-zygmund-inequality*[*OF this - integrable-measure-pmf-finite*[*OF fin*] *t*]
show *?thesis*
using *Zpos* **by** *auto*
qed

lemma *spec-chebyshev-inequality*:
assumes *fin*: *finite* (*set-pmf p*)
assumes *pvar*: *measure-pmf.variance p Y* > *0*
assumes *k*: *k* > *0*

shows
measure-pmf.prob p
{*y*. (*Y y* − *measure-pmf.expectation p Y*)^2 ≥
k^2 ∗ *measure-pmf.variance p Y*} ≤ *1* / *k*^2
proof −
define *f* **where**
f x = *Y x* / *sqrt*(*measure-pmf.variance p Y*) **for** *x*
have *1*:
measure-pmf.random-variable p borel f
by *auto*
have ∗: (λ*x*. (*f x*)^2) = (λ*x*. (*Y x*)^2/ *measure-pmf.variance p Y*)
unfolding *f-def*
by (*simp add*: *power-divide*)
have *2*:
integrable p (λ*x*. (*f x*)^2)
unfolding ∗
by (*intro integrable-measure-pmf-finite*[*OF fin*])
from
measure-pmf.Chebyshev-inequality[*OF 1 2 k*]
have *ineq1*:*measure-pmf.prob p*
{*x* . *k* ≤ |*f x* − *measure-pmf.expectation p f*|}
≤ *measure-pmf.expectation p*
(λ*x*. (*f x* − *measure-pmf.expectation p f*)^2) / *k*^{2} **by** *auto*

have (λ*x*. (*f x* − *measure-pmf.expectation p f*)^2) =
(λ*x*. ((*Y x* − *measure-pmf.expectation p Y*) / *sqrt*(*measure-pmf.variance p Y*))^2)
unfolding *f-def*
by (*simp add*: *diff-divide-distrib*)

moreover have ... = (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 / (*sqrt*(*measure-pmf.variance p Y*))^2)
by (*simp add*: *power-divide*)
moreover have ... = (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 / *measure-pmf.variance p Y*)
by *simp*
ultimately have *unfold*:(λ*x*. (*f x* − *measure-pmf.expectation p f*)^2)
= (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 / *measure-pmf.variance p Y*)
by *auto*
then have *measure-pmf.expectation p* (λ*x*. (*f x* − *measure-pmf.expectation p f*)^2) / *k*^{2}
= *measure-pmf.expectation p* (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 / *measure-pmf.variance p Y*) / *k*^{2}
by *auto*
moreover have ... = *measure-pmf.variance p Y* / *measure-pmf.variance p Y* / *k*^{2}
by *simp*
moreover have ... = *1* / *k*^{2}

using *pvar* **by** *force*
ultimately have *eq1*:*measure-pmf.expectation p* (λ*x*. (*f x* − *measure-pmf.expectation p f*)²) / *k*² = *1* / *k*²
by *auto*
have (λ*x*. *k* ≤ |*f x* − *measure-pmf.expectation p f*|) = (λ*x*. *k*² ≤ (*f x* − *measure-pmf.expectation p f*)²)
by (*metis* (*no-types*, *opaque-lifting*) *abs-of-nonneg k less-le real-le-rsqrt real-sqrt-abs sqrt-ge-absD*)
moreover have ... = (λ*x*. *k*² ≤ ((*Y x* − *measure-pmf.expectation p Y*)^2 / *measure-pmf.variance p Y*))
by (*metis unfold*)
moreover have ... = (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 ≥ *k*² ∗ *measure-pmf.variance p Y*)
by (*simp add*: *pos-le-divide-eq pvar*)
ultimately have *cond*:(λ*x*. *k* ≤ |*f x* − *measure-pmf.expectation p f*|)
= (λ*x*. (*Y x* − *measure-pmf.expectation p Y*)^2 ≥ *k*² ∗ *measure-pmf.variance p Y*)
by *auto*
show *?thesis* **using** *ineq1 cond eq1*
by *auto*
qed

end

2 Random XORs

The goal of this section is to prove that, for a randomly sampled XOR X from a set of variables V:

1. the probability of an assignment w satisfying X is $\frac{1}{2}$;
2. for any distinct assignments w, w' the probability of both satisfying X is equal to $\frac{1}{4}$ (2-wise independence); and
3. for any distinct assignments w, w', w'' the probability of all three satisfying X is equal to $\frac{1}{8}$ (3-wise independence).

theory *RandomXOR* **imports**
ApproxMCPreliminaries
Frequency-Moments.Product-PMF-Ext
Monad-Normalisation.Monad-Normalisation
begin

A random XOR constraint is modeled as a random subset of variables and a randomly chosen RHS bit.

definition *random-xor* :: *'a set* ⇒ (*'a set* × *bool*) *pmf*
where *random-xor V* =
pair-pmf (*pmf-of-set* (*Pow V*)) (*bernoulli-pmf* (*1*/*2*))

lemma *pmf-of-set-Pow-fin-map*:
assumes *V*:*finite V*
shows *pmf-of-set* (*Pow V*) =
map-pmf (λ*b*. {*x* ∈ *V*. *b x* = *Some True*})
(*Pi-pmf V def* (λ-. *map-pmf Some* (*bernoulli-pmf* (*1 / 2*))))
proof −
have ∗: *Pi-pmf V def* (λ-. *map-pmf Some* (*bernoulli-pmf* (*1 / 2*)))
=
map-pmf (λ*f x*. *if x* ∈ *V then f x else def*)
(*Pi-pmf V* (*Some False*) (λ-. *map-pmf Some* (*bernoulli-pmf* (*1 /*
2))))
unfolding *Pi-pmf-default-swap*[*OF V*] **by** *auto*

have ∗∗: *pmf-of-set* (*Pow V*) =
map-pmf
(λ*x*. {*xa*. (*xa* ∈ *V* ⟶ *x xa*) ∧ *xa* ∈ *V*})
(*Pi-pmf V False* (λ-. *bernoulli-pmf* (*1 / 2*)))
by (*smt* (*verit*, *ccfv-SIG*) *Collect-cong pmf-of-set-Pow-conv-bernoulli*
V pmf.map-cong)
show *?thesis*
unfolding ∗
apply (*subst Pi-pmf-map*[*OF V*, *of - False*])
using ∗∗ **by** (*auto simp add*: *pmf.map-comp o-def*)
qed

lemma *random-xor-from-bits*:
assumes *V*:*finite V*
shows *random-xor V* =
pair-pmf
(*map-pmf* (λ*b*. {*x* ∈ *V*. *b x* = *Some True*})
(*Pi-pmf V def* (λ-. *map-pmf Some* (*bernoulli-pmf* (*1/2*)))))
(*bernoulli-pmf* (*1/2*))
unfolding *random-xor-def*
using *V pmf-of-set-Pow-fin-map* **by** *fastforce*

fun *satisfies-xor* :: ('*a set* × *bool*) ⇒ '*a set* ⇒ *bool*
where *satisfies-xor* (*x*,*b*) ω =
even (*card* (ω ∩ *x*) + *of-bool b*)

lemma *satisfies-xor-inter*:
shows *satisfies-xor* (ω ∩ *x* ,*b*) ω = *satisfies-xor* (*x*,*b*) ω
by (*auto simp add*: *Int-commute*)

lemma *prob-bernoulli-bind-pmf*:

assumes *0 ≤ p p ≤ 1*
assumes *finite E*
shows *measure-pmf.prob*
(bernoulli-pmf p ⟜ x) E =
p ∗ (measure-pmf.prob (x True) E) +
(1 − p) ∗ (measure-pmf.prob (x False) E)
using *assms*
by (*auto simp add*: *pmf-bind measure-measure-pmf-finite*[*OF assms*(*3*)]
vector-space-over-itself.scale-sum-right comm-monoid-add-class.sum.distrib
mult.commute)

lemma *set-pmf-random-xor*:
assumes *V*: *finite V*
shows *set-pmf (random-xor V) = (Pow V) × UNIV*
unfolding *random-xor-def*
using *assms* **by** (*auto simp add*: *Pow-not-empty Set.basic-monos*(*7*))

lemma *pmf-of-set-prod*:
assumes *P ≠ {} Q ≠ {}*
assumes *finite P finite Q*
shows *pmf-of-set (P × Q) = pair-pmf (pmf-of-set P) (pmf-of-set*
Q)
by (*auto intro*!: *pmf-eqI simp add*: *indicator-def pmf-pair assms*)

lemma *random-xor-pmf-of-set*:
assumes *V*:*finite V*
shows *random-xor V = pmf-of-set ((Pow V) × UNIV)*
unfolding *random-xor-def*
apply (*subst pmf-of-set-prod*)
using *V bernoulli-pmf-half-conv-pmf-of-set* **by** *auto*

lemma *prob-random-xor-with-set-pmf*:
assumes *V*: *finite V*
shows *prob-space.prob (random-xor V) {c. P c} =*
prob-space.prob (random-xor V) {c. fst c ⊆ V ∧ P c}
by (*smt* (*verit*, *best*) *PowD assms measure-pmf.measure-pmf-eq mem-Collect-eq*
mem-Sigma-iff prod.collapse set-pmf-random-xor)

lemma *prob-set-parity*:
assumes *measure-pmf.prob M*
{c. P c} = q
shows *measure-pmf.prob M*
{c. P c = b} = (if b then q else 1 − q)
proof −
{
assume *b*:*b*
have *?thesis* **using** *assms*
using *b* **by** *presburger*
}

```
  moreover {
    assume b:¬b
    have {c. P c} ∈ measure-pmf.events M by auto
    from measure-pmf.prob-compl[OF this]
    have 1 − q = measure-pmf.prob M (UNIV − {c. P c})
      using assms by auto
    moreover have  ... =
      prob-space.prob M
      {c. P c = b}
      by (simp add: b measure-pmf.measure-pmf-eq)
    ultimately have ?thesis
      using b by presburger
  }
  ultimately show ?thesis by auto
qed

lemma satisfies-random-xor:
  assumes V: finite V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c ω} = 1 / 2
proof −
  have eq: {(c::'a set × bool). fst c ⊆ V} = {c. c ⊆ V} × UNIV
    by auto
  then have finite {(c::'a set × bool). fst c ⊆ V}
    using assms by auto

  then have ∗:
    x ⊆ V ⟹
    measure-pmf.prob (bernoulli-pmf (1 / 2) ⤜ (λy. return-pmf (x,
y)))
        {c. fst c ⊆ V ∧ satisfies-xor c ω} = 1 / 2 for x
    apply (subst prob-bernoulli-bind-pmf)
    by (auto simp add: indicator-def)

  have prob-space.prob (random-xor V) {c. satisfies-xor c ω} =
    prob-space.prob (random-xor V) {c. fst c ⊆ V ∧ satisfies-xor c ω}
    using prob-random-xor-with-set-pmf[OF V] by auto
  also have ... =
    prob-space.expectation (random-xor V)
    (indicat-real {c. fst c ⊆ V ∧ satisfies-xor c ω})
    by auto
  also have ... = (∑ a∈Pow V.
      inverse (real (card (Pow V))) ∗
      measure-pmf.prob
       (bernoulli-pmf (1 / 2) ⤜
        (λy. return-pmf (a, y)))
       {c. fst c ⊆ V ∧ satisfies-xor c ω})
    unfolding random-xor-def pair-pmf-def
    apply (subst pmf-expectation-bind-pmf-of-set)
```

```
    using assms by auto
  also have ... = (∑ a∈Pow V.
      inverse (real (card (Pow V))) * (1/2))
    by (simp add: *)
  also have ... =
      inverse (real (card (Pow V))) * (1/2) * (∑ a∈Pow V. 1)
    using * by force
  also have ... = 1/2
    by (metis One-nat-def Suc-leI assms card-Pow divide-real-def in-
verse-inverse-eq inverse-nonzero-iff-nonzero nat-one-le-power nonzero-mult-div-cancel-left
not-one-le-zero of-nat-eq-0-iff pos2 real-of-card)
  finally show ?thesis
    by presburger
qed

lemma satisfies-random-xor-parity:
  assumes V: finite V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c ω = b} = 1 / 2
  using prob-set-parity[OF satisfies-random-xor[OF V]]
    by auto
```

2.1 Independence properties of random XORs

```
lemma pmf-of-set-powerset-split:
  assumes S ⊆ V finite V
  shows
    map-pmf (λ(x,y). x ∪ y)
    (pmf-of-set (Pow S × Pow (V − S))) =
  pmf-of-set (Pow V)
proof −
  have spmfS: set-pmf (pmf-of-set (Pow S)) = Pow S
    using assms
    by (auto intro!: set-pmf-of-set simp add: rev-finite-subset)
  have spmfVS: set-pmf (pmf-of-set (Pow (V−S))) = Pow (V−S)
    using assms by (auto intro!: set-pmf-of-set)

  have xsub: x ⊆ V ⟹
        ∃ xa∈Pow S.
          ∃ y∈Pow (V − S). x = xa ∪ y for x
   by (metis Diff-subset-conv Pow-iff Un-Diff-Int basic-trans-rules(23)
inf-le2 sup-commute)

  have inj: inj-on (λ(x, y). x ∪ y)
     (Pow S × Pow (V − S))
    unfolding inj-on-def
    by auto
  then have bij: bij-betw (λ(x, y). x ∪ y)
     ((Pow S) × Pow (V − S))
```

```
    (Pow V)
    unfolding bij-betw-def
    using assms(1) xsub by (auto simp add: image-def)

  have map-pmf (λ(x, y). x ∪ y)
    (pmf-of-set (Pow S × Pow (V − S))) =
    pmf-of-set (Pow V)
    apply (subst map-pmf-of-set-inj[OF inj])
    subgoal by (auto simp add: image-def)
    subgoal using bij assms(2) bij-betw-finite by blast
    apply (intro arg-cong[where f = pmf-of-set])
    using assms(1) xsub by (auto  simp add: image-def)

  thus ?thesis
    unfolding spmfS spmfVS
    by auto
qed

lemma pmf-of-set-Pow-sing:
  showspmf-of-set (Pow {x}) =
     bernoulli-pmf (1 / 2) ⤜
     (λb. return-pmf (if b then {x} else {}))
  apply (intro pmf-eqI)
  apply (subst pmf-of-set)
 by (auto simp add: pmf-bind card-Pow indicator-def subset-singleton-iff)

lemma pmf-of-set-sing-coin-flip:
  assumes finite V
  shows pmf-of-set (Pow {x} × Pow V) =
    map-pmf (λ(r,c). (if c then {x} else {}, r)) (random-xor V)
proof −
  have ∗: pmf-of-set (Pow {x} × Pow V) =
    pair-pmf (pmf-of-set (Pow {x})) (pmf-of-set (Pow V))
    apply(intro pmf-of-set-prod)
    using assms by auto
  show ?thesis
    unfolding ∗
    apply (intro pmf-eqI)
    including monad-normalisation
   by (auto simp add: map-pmf-def pair-pmf-def random-xor-def pmf-of-set-Pow-sing)
qed


lemma measure-pmf-prob-dependent-product-bound-eq:
  assumes countable A ⋀i. countable (B i)
  assumes ⋀a. a ∈ A ⟹ measure-pmf.prob N (B a) = r
  shows measure-pmf.prob (pair-pmf M N) (Sigma A B) =
    measure-pmf.prob M A ∗ r
proof −
```

have *measure-pmf.prob* (*pair-pmf M N*) (*Sigma A B*) =
(∑ *a*(*a*, *b*) ∈ *Sigma A B*. *pmf M a* ∗ *pmf N b*)
by (*auto intro*!: *infsetsum-cong simp add*: *measure-pmf-conv-infsetsum pmf-pair*)
also have ... = (∑ *a*∈*A*. ∑ *a*∈*B a*. *pmf M a* ∗ *pmf N b*)
apply (*subst infsetsum-Sigma*[*OF assms*(1−2)])
subgoal by (*metis* (*no-types*, *lifting*) *SigmaE abs-summable-on-cong case-prod-conv pmf-abs-summable pmf-pair*)
by (*auto simp add*: *assms case-prod-unfold*)

also have ... = (∑ *a*∈*A*. *pmf M a* ∗ (*measure-pmf.prob N* (*B a*)))
by (*simp add*: *infsetsum-cmult-right measure-pmf-conv-infsetsum pmf-abs-summable*)
also have ... = (∑ *a*∈*A*. *pmf M a* ∗ *r*)
using *assms*(*3*) **by** *force*
also have... = *measure-pmf.prob M A* ∗ *r*
by (*simp add*: *infsetsum-cmult-left pmf-abs-summable measure-pmf-conv-infsetsum*)
finally show *?thesis*
by *linarith*
qed

lemma *measure-pmf-prob-dependent-product-bound-eq*′:
assumes *countable* (*A* ∩ *set-pmf M*) ⋀*i*. *countable* (*B i* ∩ *set-pmf N*)
assumes ⋀*a*. *a* ∈ *A* ∩ *set-pmf M* ⟹ *measure-pmf.prob N* (*B a* ∩ *set-pmf N*) = *r*
shows *measure-pmf.prob* (*pair-pmf M N*) (*Sigma A B*) = *measure-pmf.prob M A* ∗ *r*
proof −
have ∗: *Sigma A B* ∩ (*set-pmf M* × *set-pmf N*) =
Sigma (*A* ∩ *set-pmf M*) (λ*i*. *B i* ∩ *set-pmf N*)
by *auto*

have *measure-pmf.prob* (*pair-pmf M N*) (*Sigma A B*) =
measure-pmf.prob (*pair-pmf M N*) (*Sigma* (*A* ∩ *set-pmf M*) (λ*i*. *B i* ∩ *set-pmf N*))
by (*metis* ∗ *measure-Int-set-pmf set-pair-pmf*)
moreover have ... =
measure-pmf.prob M (*A* ∩ *set-pmf M*) ∗ *r*
using *measure-pmf-prob-dependent-product-bound-eq*[*OF assms*(1−3)]
by *auto*
moreover have ... = *measure-pmf.prob M A* ∗ *r*
by (*simp add*: *measure-Int-set-pmf*)
ultimately show *?thesis* **by** *linarith*
qed

lemma *single-var-parity-coin-flip*:
assumes *x* ∈ *ω finite ω*

```
  assumes finite a x ∉ a
  shows measure-pmf.prob (pmf-of-set (Pow {x}))
        {y. even (card ((a ∪ y) ∩ ω)) = b}  = 1/2
proof −
  have insert x a ∩ ω = insert x (a ∩ ω)
    using assms by auto
  then have ∗: card (insert x a ∩ ω) = 1 + card (a ∩ ω)
    by (simp add: assms(2) assms(4))

  have measure-pmf.prob (pmf-of-set (Pow {x}))
        {y. even (card ((a ∪ y) ∩ ω)) = b} =
    measure-pmf.prob (bernoulli-pmf (1/2))
        {odd (card (a ∩ ω)) = b}
    unfolding pmf-of-set-Pow-sing map-pmf-def[symmetric]
    by (auto intro!: measure-prob-cong-0 simp add:image-def ∗ )
  moreover have ... = 1/2
    by (simp add: measure-pmf-single)
  ultimately show ?thesis by auto
qed


lemma prob-pmf-of-set-nonempty-parity:
  assumes V: finite V
  assumes x ∈ ω ω ⊆ V
  assumes ⋀c. c ∈ E ⟷ c − {x} ∈ E
  shows prob-space.prob (pmf-of-set (Pow V))
    (E ∩ {c. even (card (c ∩ ω)) = b}) =
    1 / 2 ∗ prob-space.prob (pmf-of-set (Pow (V − {x}))) E
proof −
  have 1: set-pmf (pmf-of-set (Pow {x})) = Pow {x}
    by (simp add: Pow-not-empty)
  have 2: set-pmf (pmf-of-set (Pow (V−{x}))) = Pow (V−{x})
    by (simp add: Pow-not-empty assms(1))
  have 3: set-pmf (pmf-of-set (Pow {x} × Pow (V − {x}))) = Pow
{x} × Pow (V − {x})
    by (simp add: Pow-not-empty assms(1))

  have {x} ⊆ V using assms by auto
  from pmf-of-set-powerset-split[OF this assms(1)]
  have e: map-pmf (λ(x, y). x ∪ y)
     (pmf-of-set (Pow {x} × Pow (V − {x}))) =
    pmf-of-set (Pow V) using 1 2 by auto
  have map-pmf (λ(x, y). x ∪ y)
     (pair-pmf (pmf-of-set (Pow {x}))
       (pmf-of-set (Pow (V − {x})))) =
    map-pmf (λ(x, y). x ∪ y)
     (pair-pmf (pmf-of-set (Pow (V − {x})))
       (pmf-of-set (Pow {x})))
    apply (subst pair-commute-pmf)
```

by (*auto simp add*: *pmf.map-comp o-def case-prod-unfold Un-commute*)
then have ∗: *pmf-of-set* (*Pow V*) =
map-pmf (λ(*x*, *y*). *x* ∪ *y*)
(*pair-pmf* (*pmf-of-set* (*Pow* (*V* − {*x*}))) (*pmf-of-set* (*Pow* {*x*})))
unfolding *e*[*symmetric*]
apply (*subst pmf-of-set-prod*)
using *V* **by** *auto*

have ∗∗: ((λ(*x*, *y*). *x* ∪ *y*) −‘ (*E* ∩ *S*)) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*})
=
Sigma E (λ*x*. {*y*. (*x* ∪ *y*) ∈ *S*}) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*})
for *S*
proof −
have *11*: ⋀*a b*. *a* ∪ *b* ∈ *E* ⟹
a ∪ *b* ∈ *S* ⟹
a ⊆ *V* − {*x*} ⟹
b ⊆ {*x*} ⟹ *a* ∈ *E*
by (*metis Diff-insert-absorb Un-insert-right assms*(*4*) *boolean-algebra-cancel.sup0 subset-Diff-insert subset-singleton-iff*)

have *21*: ⋀*a b*. *a* ∈ *E* ⟹
a ∪ *b* ∈ *S* ⟹
a ⊆ *V* − {*x*} ⟹
b ⊆ {*x*} ⟹ *a* ∪ *b* ∈ *E*
by (*metis Diff-cancel Un-Diff Un-empty-left assms*(*4*) *inf-sup-aci*(*5*) *subset-singletonD*)

have *1*:
⋀*ab*. *ab* ∈ ((λ(*x*, *y*). *x* ∪ *y*) −‘ (*E* ∩ *S*)) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*}) ⟹
ab ∈ *Sigma E* (λ*x*. {*y*. (*x* ∪ *y*) ∈ *S*}) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*})
using *11* **by** *clarsimp*

also have *2*:
⋀*ab*. *ab* ∈ *Sigma E* (λ*x*. {*y*. (*x* ∪ *y*) ∈ *S*}) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*}) ⟹
ab ∈ ((λ(*x*, *y*). *x* ∪ *y*) −‘ (*E* ∩ *S*)) ∩ (*Pow* (*V* − {*x*}) × *Pow*{*x*})
using *21* **by** *clarsimp*
ultimately show *?thesis*
apply (*intro antisym*)
by (*meson subsetI*)+
qed

have *eR*: ⋀*a*. *a* ∈ *E* ∩ *set-pmf* (*pmf-of-set* (*Pow* (*V* − {*x*}))) ⟹
measure-pmf.prob (*pmf-of-set* (*Pow* {*x*}))
({*y*. *even* (*card* ((*a* ∪ *y*) ∩ ω)) = *b*} ∩
set-pmf (*pmf-of-set* (*Pow* {*x*}))) = *1*/*2*

```
    apply (subst measure-Int-set-pmf)
    apply (intro single-var-parity-coin-flip)
    subgoal using assms by clarsimp
    subgoal using assms rev-finite-subset by blast
   subgoal by (metis 2 IntD2 PowD assms(1) finite-Diff rev-finite-subset)
    using 2 by blast

  have
    prob-space.prob (pmf-of-set (Pow V))
      (E ∩ {c. even (card (c ∩ ω)) = b}) =
    prob-space.prob (map-pmf (λ(x, y). x ∪ y)
     (pair-pmf (pmf-of-set (Pow (V − {x}))) (pmf-of-set (Pow {x}))))
      (E ∩ {c. even (card (c ∩ ω)) = b}) unfolding ∗ by auto
  moreover have ... =
   prob-space.prob (pair-pmf (pmf-of-set (Pow (V − {x}))) (pmf-of-set
(Pow {x})))
      ((λ(x, y). x ∪ y) −‘ (E ∩ {c. even (card (c ∩ ω)) = b}))
    by auto
  moreover have ... =
   prob-space.prob (pair-pmf (pmf-of-set (Pow (V − {x}))) (pmf-of-set
(Pow {x})))
    ((λ(x, y). x ∪ y) −‘ (E ∩ {c. even (card (c ∩ ω)) = b}) ∩ (Pow
(V − {x}) × Pow{x}))
   by (smt (verit) 1 2 Int-iff Sigma-cong measure-pmf.measure-pmf-eq
set-pair-pmf)
  moreover have ... =
   prob-space.prob (pair-pmf (pmf-of-set (Pow (V − {x}))) (pmf-of-set
(Pow {x})))
    (Sigma E (λx. {y. even (card ((x ∪ y) ∩ ω)) = b}) ∩ (Pow (V −
{x}) × Pow{x}))
    unfolding ∗∗ by auto
  moreover have ... =
   prob-space.prob (pair-pmf (pmf-of-set (Pow (V − {x}))) (pmf-of-set
(Pow {x})))
    (Sigma E (λx. {y. even (card ((x ∪ y) ∩ ω)) = b}))
   by (smt (verit, best) 1 2 Int-iff Sigma-cong measure-pmf.measure-pmf-eq
set-pair-pmf)
  moreover have ... =
    measure-pmf.prob (pmf-of-set (Pow (V − {x}))) E ∗
    (1 / 2)
    apply (subst measure-pmf-prob-dependent-product-bound-eq'[OF -
- eR])
    by auto
  ultimately show ?thesis by auto
qed

lemma prob-random-xor-split:
  assumes V: finite V
  shows prob-space.prob (random-xor V) E =
```

```
    1 / 2 * prob-space.prob (pmf-of-set (Pow V)) {e. (e,True) ∈ E} +
    1 / 2 * prob-space.prob (pmf-of-set (Pow V)) {e. (e,False) ∈ E}
proof −
  have fin: finite (set-pmf (random-xor V))
    by (simp add: V set-pmf-random-xor)

  have fin2: finite ((λ(x, y). (y, x)) −‘ set-pmf (random-xor V))
    by(auto intro!: finite-vimageI[OF fin] simp add: inj-def)

  have rw: {x. (x, b) ∈ E ∧ (x, b) ∈ set-pmf (random-xor V)} =
    {x. (x,b) ∈ E} ∩ set-pmf (pmf-of-set (Pow V)) for b
    by (auto simp add: V set-pmf-random-xor Pow-not-empty)

  have prob-space.prob (random-xor V) E =
    prob-space.prob (random-xor V) (E ∩ set-pmf (random-xor V))
    by (simp add: measure-Int-set-pmf)

  moreover have ... =
     measure-pmf.prob
     (pair-pmf (bernoulli-pmf (1 / 2))
       (pmf-of-set (Pow V)))
     ((λ(x, y). (y, x)) −‘ (E ∩ set-pmf (random-xor V)))
    unfolding random-xor-def
    apply (subst pair-commute-pmf)
    by simp
  moreover have ... =
    1 / 2 *
      measure-pmf.prob (pmf-of-set (Pow V)) {x. (x, True) ∈ E} +
    1 / 2 *
      measure-pmf.prob (pmf-of-set (Pow V)) {x. (x, False) ∈ E}
    unfolding pair-pmf-def
    apply (subst prob-bernoulli-bind-pmf)
    using fin2
    unfolding map-pmf-def[symmetric] measure-map-pmf
    by (auto simp add: vimage-def rw simp add: measure-Int-set-pmf)
  ultimately show ?thesis by auto
qed

lemma prob-random-xor-nonempty-parity:
  assumes V: finite V
  assumes ω: x ∈ ω ω ⊆ V
  assumes E: ⋀c. c ∈ E ⟷ (fst c − {x},snd c) ∈ E
  shows prob-space.prob (random-xor V)
    (E ∩ {c. satisfies-xor c ω = b}) =
    1 / 2 * prob-space.prob (random-xor (V − {x})) E
proof −
  have ∗: {e. (e, b′) ∈ E ∩ {c. satisfies-xor c ω = b}} =
    {e. (e, b′) ∈ E} ∩ {c. even (card (c ∩ ω)) = (b ≠ b′)} for b′
    by (auto simp add: Int-commute)
```

```
  have prob-space.prob (random-xor V)
    (E ∩ {c. satisfies-xor c ω = b}) =
    1 / 2 *
    measure-pmf.prob (pmf-of-set (Pow V))
     {e. (e, True) ∈ E ∩ {c. satisfies-xor c ω = b}} +
    1 / 2 *
    measure-pmf.prob (pmf-of-set (Pow V))
     {e. (e, False) ∈ E ∩ {c. satisfies-xor c ω = b}}
    unfolding prob-random-xor-split[OF V] by auto
  also have ... =
    1 / 2 *
    measure-pmf.prob (pmf-of-set (Pow V))
     ({e. (e, True) ∈ E} ∩ {c. even (card (c ∩ ω)) = (b ≠ True)}) +
    1 / 2 *
    measure-pmf.prob (pmf-of-set (Pow V))
     ({e. (e, False) ∈ E} ∩ {c. even (card (c ∩ ω)) = (b ≠ False)})
    unfolding * by auto
  also have ... =
    1 / 2 *
    (1 / 2 *
     measure-pmf.prob (pmf-of-set (Pow (V − {x})))
      {e. (e, True) ∈ E} +
     1 / 2 *
     measure-pmf.prob (pmf-of-set (Pow (V − {x}))))
      {e. (e, False) ∈ E})
    apply (subst prob-pmf-of-set-nonempty-parity[OF V ω])
    subgoal using E by clarsimp
    apply (subst prob-pmf-of-set-nonempty-parity[OF V ω])
    using E by auto
  also have ... =
    1 / 2 * measure-pmf.prob (random-xor (V − {x})) E
    apply (subst prob-random-xor-split[symmetric])
    using V by auto
  finally show ?thesis by auto
qed

lemma pair-satisfies-random-xor-parity-1:
  assumes V:finite V
  assumes x: x ∉ ω x ∈ ω'
  assumes ω: ω ⊆ V ω' ⊆ V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c ω = b ∧ satisfies-xor c ω' = b'} = 1 / 4
proof −
  have wa: ω ∩ (a − {x}) = ω ∩ a for a
    using x
    by blast
  have prob-space.prob (random-xor V)
    {c. satisfies-xor c ω = b ∧ satisfies-xor c ω' = b'} =
```

```
    prob-space.prob (random-xor V)
    ({c. satisfies-xor c ω = b} ∩ {c. satisfies-xor c ω' = b'})
    by (simp add: Collect-conj-eq)
  also have ... =
    1 / 2 *
    measure-pmf.prob (random-xor (V - {x})) {c. satisfies-xor c ω =
b}
    apply (subst prob-random-xor-nonempty-parity[OF V x(2) ω(2)])
    by (auto simp add: wa)
  also have ... = 1/4
    apply (subst satisfies-random-xor-parity)
    using V by auto
  finally show ?thesis by auto
qed

lemma pair-satisfies-random-xor-parity:
  assumes V:finite V
  assumes ω: ω ≠ ω' ω ⊆ V ω' ⊆ V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c ω = b ∧ satisfies-xor c ω' = b'} = 1 / 4
proof -
  obtain x where x ∉ ω ∧ x ∈ ω' ∨ x ∉ ω' ∧ x ∈ ω
    using ω
    by blast
  moreover {
    assume x: x ∉ ω x ∈ ω'
   have ?thesis using pair-satisfies-random-xor-parity-1[OF V x ω(2-3)]
      by blast
  }
  moreover {
    assume x: x ∉ ω' x ∈ ω
    then have ?thesis using pair-satisfies-random-xor-parity-1[OF V
x ω(3) ω(2)]
      by (simp add: Collect-conj-eq Int-commute)
  }
  ultimately show ?thesis by auto
qed

lemma prob-pmf-of-set-nonempty-parity-UNIV:
  assumes finite V
  assumes x ∈ ω ω ⊆ V
  shows prob-space.prob (pmf-of-set (Pow V))
    {c. even (card (c ∩ ω)) = b} = 1 / 2
  using prob-pmf-of-set-nonempty-parity[OF assms, of UNIV]
  by auto

lemma prob-Pow-split:
  assumes ω ⊆ V finite V
  shows prob-space.prob (pmf-of-set (Pow V))
```

```
    {x. P (ω ∩ x) ∧ Q ((V − ω) ∩ x)} =
  prob-space.prob (pmf-of-set (Pow ω))
    {x. P x} ∗
  prob-space.prob (pmf-of-set (Pow (V − ω)))
    {x. Q x}
proof −
  have 1: set-pmf (pmf-of-set (Pow ω)) = Pow ω
     by (meson Pow-not-empty assms(1) assms(2) finite-Pow-iff fi-
nite-subset set-pmf-of-set)
  have 2: set-pmf
        (pmf-of-set (Pow (V − ω))) = Pow (V − ω )
    by (simp add: Pow-not-empty assms(2))

  have ∗: (pmf-of-set (Pow ω × Pow (V − ω))) =
     (pair-pmf (pmf-of-set (Pow ω)) (pmf-of-set (Pow (V − ω))))
    unfolding 1 2
    apply (subst pmf-of-set-prod)
    using assms rev-finite-subset by auto
  have ∗∗: (((λ(x, y). x ∪ y) −‘
      {x. P (ω ∩ x) ∧ Q ((V − ω) ∩ x)}) ∩ ((Pow ω) × (Pow (V −
ω)))) =
    ({x. P x} ∩ Pow ω) × ({x. Q x} ∩ Pow (V − ω))
    apply (rule antisym)
    subgoal
      apply clarsimp
     by (smt (verit) Diff-disjoint Int-Un-eq(4) inf.orderE inf-commute
inf-sup-distrib1 sup-bot.right-neutral sup-commute)
    apply (intro subsetI)
    apply clarsimp
     by (smt (verit, ccfv-threshold) Diff-Int Diff-disjoint Diff-empty
Diff-eq-empty-iff Un-Int-assoc-eq Un-commute sup-bot.left-neutral)

  have prob-space.prob (pmf-of-set (Pow V))
    {x. P (ω ∩ x) ∧ Q ((V − ω) ∩ x)} =
    prob-space.prob (map-pmf (λ(x,y). x ∪ y)
      (pmf-of-set (Pow ω × Pow (V − ω))))
    {x. P (ω ∩ x) ∧  Q ((V − ω) ∩ x)}
   apply (subst pmf-of-set-powerset-split[symmetric, OF assms(1−2)])
    by auto
  moreover have ... =
    measure-pmf.prob
     (pair-pmf (pmf-of-set (Pow ω)) (pmf-of-set (Pow (V − ω))))
     ((λ(x, y). x ∪ y) −‘
      {x. P (ω ∩ x) ∧ Q ((V − ω) ∩ x)})
    unfolding measure-map-pmf
    using ∗
    by presburger
  moreover have ... =
    measure-pmf.prob
```

(*pair-pmf* (*pmf-of-set* (*Pow* ω)) (*pmf-of-set* (*Pow* (V − ω))))
(((λ(x, y). $x \cup y$) −‘
{x. P ($\omega \cap x$) ∧ Q ((V − ω) ∩ x)}) ∩ ((*Pow* ω) × (*Pow* (V − ω))))
using *1 2*
by (*smt* (*verit*) *Int-Collect Int-def Sigma-cong inf-idem measure-pmf.measure-pmf-eq set-pair-pmf*)
moreover have ... =
measure-pmf.prob
(*pair-pmf* (*pmf-of-set* (*Pow* ω)) (*pmf-of-set* (*Pow* (V − ω))))
(({x. P x} ∩ *Pow* ω) × ({x. Q x} ∩ *Pow* (V − ω)))
unfolding $**$
by *auto*
moreover have ... =
measure-pmf.prob
(*pmf-of-set* (*Pow* ω)) ({x. P x} ∩ *Pow* ω) $*$
measure-pmf.prob
(*pmf-of-set* (*Pow* (V − ω))) ({x. Q x} ∩ *Pow* (V − ω))
apply (*intro measure-pmf-prob-product*)
subgoal by (*meson assms*(*1*) *assms*(*2*) *countable-finite finite-Int finite-Pow-iff rev-finite-subset*)
by (*simp add*: *assms*(*2*) *countable-finite*)
moreover have ... =
measure-pmf.prob
(*pmf-of-set* (*Pow* ω)) {x. P x} $*$
measure-pmf.prob
(*pmf-of-set* (*Pow* (V − ω))) {x. Q x}
by (*metis 1 2 measure-Int-set-pmf*)
ultimately show *?thesis* **by** *auto*
qed

lemma *disjoint-prob-pmf-of-set-nonempty*:
assumes ω: $x \in \omega$ $\omega \subseteq V$
assumes ω': $x' \in \omega'$ $\omega' \subseteq V$
assumes $\omega \cap \omega' = \{\}$
assumes V: *finite* V
shows *prob-space.prob* (*pmf-of-set* (*Pow* V))
{c. *even* (*card* ($\omega \cap c$)) = b ∧ *even* (*card* ($\omega' \cap c$)) = b'} = *1* / *4*
proof −
have *prob-space.prob* (*pmf-of-set* (*Pow* V))
{c. *even* (*card* ($\omega \cap c$)) = b ∧ *even* (*card* ($\omega' \cap c$)) = b'} =
prob-space.prob (*pmf-of-set* (*Pow* V))
{c. *even* (*card* ($\omega \cap c$)) = b ∧ *even* (*card* ((((V − ω) ∩ c) ∩ ω')) = b'}
by (*smt* (*verit*) *Collect-cong Diff-Diff-Int Diff-eq-empty-iff Int-Diff Int-commute* ω'(*2*) *assms*(*5*) *inf.orderE*)

moreover have ... =

```
    measure-pmf.prob (pmf-of-set (Pow ω))
     {x. even (card x) = b} *
    measure-pmf.prob (pmf-of-set (Pow (V − ω)))
     {x. even (card (x ∩ ω')) = b'}
    apply (subst prob-Pow-split)
    using assms by auto
  moreover have ... =
    measure-pmf.prob (pmf-of-set (Pow ω))
     {x. even (card (x ∩ ω)) = b} *
    measure-pmf.prob (pmf-of-set (Pow (V − ω)))
     {x. even (card (x ∩ ω')) = b'}
      by (smt (verit, best) PowD Pow-not-empty ω(2) assms(6) finite-Pow-iff inf.orderE measure-pmf.measure-pmf-eq mem-Collect-eq rev-finite-subset set-pmf-of-set)

   moreover have ... = 1/4
    apply (subst prob-pmf-of-set-nonempty-parity-UNIV[OF - ω(1)])
     subgoal using assms rev-finite-subset by blast
     subgoal by simp
    apply (subst prob-pmf-of-set-nonempty-parity-UNIV)
    using assms by auto
  ultimately show ?thesis by auto
qed

lemma measure-pmf-prob-product-finite-set-pmf:
  assumes finite (set-pmf M) finite (set-pmf N)
  shows measure-pmf.prob (pair-pmf M N) (A × B) =
  measure-pmf.prob M A * measure-pmf.prob N B
proof −
  have A: measure-pmf.prob M A = measure-pmf.prob M (A ∩ set-pmf M)
    by (simp add: measure-Int-set-pmf)
  have B: measure-pmf.prob N B = measure-pmf.prob N (B ∩ set-pmf N)
    by (simp add: measure-Int-set-pmf)
  have measure-pmf.prob M A * measure-pmf.prob N B =
    measure-pmf.prob M (A ∩ set-pmf M) *  measure-pmf.prob N (B ∩ set-pmf N)
    using A B by auto
  moreover have ... = measure-pmf.prob (pair-pmf M N)
     ((A ∩ set-pmf M) × (B ∩ set-pmf N))
    apply (subst measure-pmf-prob-product[symmetric])
    by auto
  moreover have ... = measure-pmf.prob (pair-pmf M N)
     ((A × B) ∩ set-pmf (pair-pmf M N))
    by (simp add: Times-Int-Times)
  moreover have ... = measure-pmf.prob (pair-pmf M N)
     ((A × B) )
    using measure-Int-set-pmf by blast
```

ultimately show *?thesis* **by** *auto*
qed

lemma *prob-random-xor-split-space*:
assumes $\omega \subseteq V$ *finite* V
shows *prob-space.prob* (*random-xor* V)
$\{(x,b).\ P\ (\omega \cap x)\ b \wedge Q\ ((V - \omega) \cap x)\} =$
prob-space.prob (*random-xor* ω)
$\{(x,b).\ P\ x\ b\} *$
prob-space.prob (*pmf-of-set* (*Pow* $(V - \omega)$))
$\{x.\ Q\ x\}$
proof −
have *d1*: *set-pmf* (*random-xor* ω) = *Pow* $\omega \times$ *UNIV*
by (*metis assms*(*1*) *assms*(*2*) *infinite-super set-pmf-random-xor*)
have *d2*: *set-pmf* (*pmf-of-set* (*Pow* $(V - \omega)$)) = *Pow* $(V- \omega)$
by (*simp add*: *Pow-not-empty assms*(*2*))
have *rhs*: *prob-space.prob* (*random-xor* ω)
$\{(x,b).\ P\ x\ b\} *$
prob-space.prob (*pmf-of-set* (*Pow* $(V - \omega)$))
$\{x.\ Q\ x\} =$
prob-space.prob (*pair-pmf* (*random-xor* ω) (*pmf-of-set* (*Pow* $(V - \omega)$)))
$(\{(x,b).\ P\ x\ b\} \times \{x.\ Q\ x\})$
apply (*subst measure-pmf-prob-product-finite-set-pmf*)
subgoal by (*metis Pow-def assms*(*1*) *assms*(*2*) *finite-Collect-subsets finite-SigmaI finite-code rev-finite-subset set-pmf-random-xor*)
using *assms* **by** (*auto simp add*: *Pow-not-empty*)

from *pmf-of-set-powerset-split*[*OF assms*]
have $*$: *pmf-of-set* (*Pow* V) =
map-pmf $(\lambda(x,\ y).\ x \cup y)$
(*pair-pmf* (*pmf-of-set* (*Pow* ω)) (*pmf-of-set* (*Pow* $(V - \omega)$)))
by (*metis Pow-not-empty assms*(*1*) *assms*(*2*) *finite-Diff finite-Pow-iff pmf-of-set-prod rev-finite-subset*)

have $**$: *random-xor* V =
map-pmf $(\lambda((x,b),y).\ (x \cup y,b))$ (*pair-pmf* (*random-xor* ω) (*pmf-of-set* (*Pow* $(V - \omega)$)))
unfolding *random-xor-def* $*$
including *monad-normalisation*
by (*auto simp add*: *pair-pmf-def map-pmf-def case-prod-unfold*)

have *prob-space.prob* (*random-xor* V) $\{(x,b).\ P\ (\omega \cap x)\ b \wedge Q\ ((V - \omega) \cap x)\} =$
measure-pmf.prob
(*pair-pmf* (*random-xor* ω) (*pmf-of-set* (*Pow* $(V - \omega)$)))
$\{y.\ P\ (\omega \cap (fst\ (fst\ y) \cup snd\ y))\ (snd\ (fst\ y)) \wedge$
$Q\ ((V - \omega) \cap (fst\ (fst\ y) \cup snd\ y))\}$
unfolding $**$

by (*auto simp add*:*case-prod-unfold*)

moreover have ... =
prob-space.prob (*pair-pmf* (*random-xor* ω) (*pmf-of-set* (*Pow* (V − ω))))
({(*x*,*b*). *P x b*} × {*x*. *Q x*})
apply (*intro measure-pmf.measure-pmf-eq*[**where** *p* =*pair-pmf* (*random-xor* ω)
(*pmf-of-set* (*Pow* (V − ω)))])
subgoal by *simp*
apply (*clarsimp simp add*: *d1 d2*)
by (*smt* (*verit*, *del-insts*) *Diff-disjoint Int-Diff boolean-algebra-cancel.sup0 inf.orderE inf-commute inf-sup-distrib1 sup-bot.left-neutral*)
ultimately show *?thesis* **using** *rhs*
by *simp*
qed

lemma *three-disjoint-prob-random-xor-nonempty*:
assumes ω: $\omega \neq \{\}$ $\omega \subseteq V$
assumes ω': $\omega' \neq \{\}$ $\omega' \subseteq V$
assumes I: $I \subseteq V$
assumes *int*: $I \cap \omega = \{\}$ $I \cap \omega' = \{\}$ $\omega \cap \omega' = \{\}$
assumes V: *finite* V
shows *prob-space.prob* (*random-xor* V)
{*c*. *satisfies-xor c I* = *b* ∧
even (*card* (ω ∩ *fst c*)) = b' ∧
even (*card* (ω' ∩ *fst c*)) = b''} = *1* / *8*
proof −
have *finI*: *finite I*
using *V I*
using *rev-finite-subset* **by** *blast*
have *finVI*: *finite* (V − I)
using *V I*
using *rev-finite-subset* **by** *blast*
obtain *x x'* **where** *x*: $x \in \omega$ $x' \in \omega'$ **using** ω ω'
by *blast*

have *rw1*:$\omega \cap ((V - I) \cap xx) = \omega \cap xx$ **for** *xx*
by (*metis Diff-Int-distrib2 Diff-empty* ω(*2*) *assms*(*6*) *inf.absorb-iff2 inf-assoc inf-left-commute*)

have *rw2*:$\omega' \cap ((V - I) \cap xx) = \omega' \cap xx$ **for** *xx*
by (*metis Diff-Int-distrib2 Diff-empty* ω'(*2*) *assms*(*7*) *inf.absorb-iff2 inf-assoc inf-left-commute*)

have *prob-space.prob* (*random-xor* V)
{*c*. *satisfies-xor c I* = *b* ∧
even (*card* (ω ∩ *fst c*)) = b' ∧
even (*card* (ω' ∩ *fst c*)) = b''} =

```
    prob-space.prob (random-xor V)
    {(x,bb). satisfies-xor (I ∩ x, bb) I = b ∧
      even (card (ω ∩ ((V − I) ∩ x))) = b' ∧
      even (card ( ω' ∩ ((V − I) ∩ x))) = b''}
   apply (intro arg-cong[where f = prob-space.prob (random-xor V)])
    unfolding rw1 rw2 satisfies-xor-inter
    by (smt (verit) Collect-cong prod.collapse split-conv)

  moreover have ... =
    measure-pmf.prob (random-xor I)
     {c. satisfies-xor c I = b} *
    measure-pmf.prob (pmf-of-set (Pow (V − I)))
     {x. even (card (ω ∩ x)) = b' ∧
         even (card (ω' ∩ x)) = b''}
    apply (subst prob-random-xor-split-space[OF I V])
    by (metis (no-types, lifting) Collect-cong case-prodE case-prodI2)
  moreover have ... = 1 / 8
    apply (subst satisfies-random-xor-parity[OF finI])
    apply (subst disjoint-prob-pmf-of-set-nonempty)
    using x ω ω' int finVI by auto
  ultimately show ?thesis by auto
qed


lemma three-disjoint-prob-pmf-of-set-nonempty:
  assumes ω: x ∈ ω ω ⊆ V
  assumes ω': x' ∈ ω' ω' ⊆ V
  assumes ω'': x'' ∈ ω'' ω'' ⊆ V
  assumes int: ω ∩ ω' = {} ω' ∩ ω'' = {} ω'' ∩ ω = {}
  assumes V: finite V
  shows prob-space.prob (pmf-of-set (Pow V))
    {c. even (card (ω ∩ c)) = b ∧ even (card (ω' ∩ c)) = b' ∧ even
(card (ω'' ∩ c)) = b''} = 1 / 8
proof −
  have prob-space.prob (pmf-of-set (Pow V))
    {c. even (card (ω ∩ c)) = b ∧ even (card (ω' ∩ c)) = b' ∧ even
(card (ω'' ∩ c)) = b''} =
    prob-space.prob (pmf-of-set (Pow V))
    {c. even (card (ω ∩ c)) = b ∧
       even (card (((V − ω) ∩ c) ∩ ω')) = b' ∧
       even (card (((V − ω) ∩ c) ∩ ω'')) = b''}
     by (smt (verit,best) Collect-cong Diff-Diff-Int Diff-eq-empty-iff
Int-Diff Int-commute ω' ω'' int inf.orderE)

  moreover have ... =
    measure-pmf.prob (pmf-of-set (Pow ω))
     {x. even (card x) = b} *
    measure-pmf.prob (pmf-of-set (Pow (V − ω)))
     {x. even (card (ω' ∩ x)) = b' ∧ even (card (ω'' ∩ x)) = b''}
```

```
    apply (subst prob-Pow-split)
    using assms by (auto simp add: inf.commute)
  moreover have ... =
    measure-pmf.prob (pmf-of-set (Pow ω))
     {x. even (card (x ∩ ω)) = b} *
    measure-pmf.prob (pmf-of-set (Pow (V − ω)))
     {x. even (card (ω' ∩ x)) = b' ∧ even (card (ω'' ∩ x)) = b''}
      by (smt (verit, best) PowD Pow-not-empty ω V finite-Pow-iff
inf.orderE measure-pmf.measure-pmf-eq mem-Collect-eq rev-finite-subset
set-pmf-of-set)

   moreover have ... = 1/8
    apply (subst prob-pmf-of-set-nonempty-parity-UNIV[OF - ω(1)])
     subgoal using ω(2) V rev-finite-subset by blast
     subgoal by simp
     apply (subst disjoint-prob-pmf-of-set-nonempty)
     using assms by auto
  ultimately show ?thesis by auto
qed

lemma four-disjoint-prob-random-xor-nonempty:
  assumes ω: ω ≠ {} ω ⊆ V
  assumes ω': ω' ≠ {} ω' ⊆ V
  assumes ω'': ω'' ≠ {} ω'' ⊆ V
  assumes I: I ⊆ V
  assumes int: I ∩ ω = {} I ∩ ω' = {} I ∩ ω'' = {}
    ω ∩ ω' = {} ω' ∩ ω'' = {} ω'' ∩ ω = {}
  assumes V: finite V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c I = b0 ∧
      even (card (ω ∩ fst c)) = b ∧
      even (card (ω' ∩ fst c)) = b' ∧
      even (card (ω'' ∩ fst c)) = b''} = 1 / 16
proof −
  have finI: finite I
    using V I
    using rev-finite-subset by blast
  have finVI: finite (V − I)
    using V I
    using rev-finite-subset by blast
  obtain x x' x'' where x: x ∈ ω x' ∈ ω' x'' ∈ ω''
    using ω ω' ω''
    by blast

  have rw1:ω ∩ ((V − I) ∩ xx) = ω ∩  xx for xx
    by (metis Diff-Int-distrib2 Diff-empty ω(2) int(1) inf.absorb-iff2
inf-assoc inf-left-commute)

  have rw2:ω' ∩ ((V − I) ∩ xx)= ω' ∩  xx for xx
```

by (*metis Diff-Int-distrib2 Diff-empty* $\omega'(2)$ *int*(2) *inf.absorb-iff2 inf-assoc inf-left-commute*)

have *rw3*:$\omega'' \cap ((V - I) \cap xx) = \omega'' \cap \ xx$ **for** *xx*
by (*metis Diff-Int-distrib2 Diff-empty* $\omega''(2)$ *int*(3) *inf.absorb-iff2 inf-assoc inf-left-commute*)

have *prob-space.prob* (*random-xor V*)
{*c*. *satisfies-xor c I* = *b0* ∧
even (*card* (ω ∩ *fst c*)) = *b* ∧
even (*card* (ω' ∩ *fst c*)) = b' ∧
even (*card* (ω'' ∩ *fst c*)) = b''} =
prob-space.prob (*random-xor V*)
{(*x*,*bb*). *satisfies-xor* (*I* ∩ *x*, *bb*) *I* = *b0* ∧
even (*card* (ω ∩ ((*V* − *I*) ∩ *x*))) = *b* ∧
even (*card* (ω' ∩ ((*V* − *I*) ∩ *x*))) = b' ∧
even (*card* (ω'' ∩ ((*V* − *I*) ∩ *x*))) = b''}
apply (*intro arg-cong*[**where** *f* = *prob-space.prob* (*random-xor V*)])
unfolding *rw1 rw2 rw3 satisfies-xor-inter*
by (*smt* (*verit*) *Collect-cong prod.collapse split-conv*)

moreover have ... =
measure-pmf.prob (*random-xor I*)
{*c*. *satisfies-xor c I* = *b0*} ∗
measure-pmf.prob (*pmf-of-set* (*Pow* (*V* − *I*)))
{*x*. *even* (*card* (ω ∩ *x*)) = *b* ∧
even (*card* (ω' ∩ *x*)) = b' ∧
even (*card* (ω'' ∩ *x*)) = b''}
apply (*subst prob-random-xor-split-space*[*OF I V*])
by (*metis* (*no-types*, *lifting*) *Collect-cong case-prodE case-prodI2*)
moreover have ... = *1* / *16*
apply(*subst satisfies-random-xor-parity*[*OF finI*])
apply (*subst three-disjoint-prob-pmf-of-set-nonempty*)
using *x* ω ω' ω'' *int finVI* **by** *auto*
ultimately show *?thesis* **by** *auto*
qed

lemma *three-satisfies-random-xor-parity-1*:
assumes *V*:*finite V*
assumes ω: ω ⊆ *V* ω' ⊆ *V* ω'' ⊆ *V*
assumes *x*: *x* ∉ ω *x* ∉ ω' *x* ∈ ω''
assumes *d*: ω ≠ ω'
shows *prob-space.prob* (*random-xor V*)
{*c*.
satisfies-xor c ω = *b* ∧
satisfies-xor c ω' = b' ∧
satisfies-xor c ω'' = b''} = *1* / *8*
proof −
have *wa*: ω ∩ (*a* − {*x*}) = ω ∩ *a* **for** *a*

```
    using x
    by blast
  have wa': ω' ∩ (a − {x}) = ω' ∩ a for a
    using x
    by blast
  have prob-space.prob (random-xor V)
    {c.
      satisfies-xor c ω = b ∧ satisfies-xor c ω' = b' ∧
      satisfies-xor c ω'' = b''} =
    prob-space.prob (random-xor V)
    ({c. satisfies-xor c ω = b ∧ satisfies-xor c ω' = b'} ∩
      {c. satisfies-xor c ω'' = b''})
    by (simp add: Collect-conj-eq inf-assoc)
  moreover have ... =
    1 / 2 *
    measure-pmf.prob (random-xor (V − {x}))
      {c. satisfies-xor c ω = b ∧ satisfies-xor c ω' = b'}
    apply (subst prob-random-xor-nonempty-parity[OF V x(3) ω(3)])
    by (auto simp add: wa wa')
  moreover have ... = 1/8
    apply (subst pair-satisfies-random-xor-parity)
    using V ω x d by auto
  ultimately show ?thesis by auto
qed

lemma split-boolean-eq:
  shows(A ⟷ B) = (b ⟷ I) ∧
    (B ⟷ C) = (b' ⟷  I) ∧
    (C ⟷ A) = (b'' ⟷ I)
  ⟷
    I = odd(of-bool b + of-bool b' + of-bool b'') ∧
     (A = True ∧
      B = (b'=b'') ∧
      C = (b = b') ∨
      A = False ∧
      B = (b' ≠ b'') ∧
      C = (b ≠ b'))
  by auto

lemma three-satisfies-random-xor-parity:
  assumes V:finite V
  assumes ω:
      ω ≠ ω' ω ≠ ω'' ω' ≠ ω''
      ω ⊆ V ω' ⊆ V ω'' ⊆ V
  shows prob-space.prob (random-xor V)
    {c. satisfies-xor c ω = b ∧
        satisfies-xor c ω' = b' ∧
        satisfies-xor c ω'' = b''} = 1 / 8
proof −
```

have ($\exists\, x.$
$x \in \omega \wedge x \notin \omega' \wedge x \notin \omega'' \vee$
$x \in \omega' \wedge x \notin \omega \wedge x \notin \omega'' \vee$
$x \in \omega'' \wedge x \notin \omega \wedge x \notin \omega') \vee$
$\omega - (\omega' \cup \omega'') = \{\} \wedge$
$\omega' - (\omega \cup \omega'') = \{\} \wedge$
$\omega'' - (\omega \cup \omega') = \{\}$
by *blast*
moreover {
assume ($\exists\, x.$
$x \in \omega \wedge x \notin \omega' \wedge x \notin \omega'' \vee$
$x \in \omega' \wedge x \notin \omega \wedge x \notin \omega'' \vee$
$x \in \omega'' \wedge x \notin \omega \wedge x \notin \omega'$)
then obtain x **where**
$x \in \omega \wedge x \notin \omega' \wedge x \notin \omega'' \vee$
$x \in \omega' \wedge x \notin \omega \wedge x \notin \omega'' \vee$
$x \in \omega'' \wedge x \notin \omega \wedge x \notin \omega'$ **by** *auto*
moreover {
assume x: $x \notin \omega'$ $x \notin \omega''$ $x \in \omega$
have *measure-pmf.prob* (*random-xor V*)
{*c. satisfies-xor c* $\omega' = b' \wedge$
satisfies-xor c $\omega'' = b'' \wedge$
satisfies-xor c $\omega = b$} = *1 / 8*
apply (*intro three-satisfies-random-xor-parity-1*[*OF V - - - x*])
using ω **by** *auto*
then have *?thesis*
by (*smt* (*verit*, *ccfv-SIG*) *Collect-cong*)
}
moreover {
assume x: $x \notin \omega$ $x \notin \omega''$ $x \in \omega'$
have *measure-pmf.prob* (*random-xor V*)
{*c. satisfies-xor c* $\omega = b \wedge$
satisfies-xor c $\omega'' = b'' \wedge$
satisfies-xor c $\omega' = b'$} = *1 / 8*
apply (*intro three-satisfies-random-xor-parity-1*[*OF V - - - x*])
using ω **by** *auto*
then have *?thesis*
by (*smt* (*verit*, *ccfv-SIG*) *Collect-cong*)
}
moreover {
assume x: $x \notin \omega$ $x \notin \omega'$ $x \in \omega''$
have *measure-pmf.prob* (*random-xor V*)
{*c. satisfies-xor c* $\omega = b \wedge$
satisfies-xor c $\omega' = b' \wedge$
satisfies-xor c $\omega'' = b''$} = *1 / 8*
apply (*intro three-satisfies-random-xor-parity-1*[*OF V - - - x*])
using ω **by** *auto*
then have *?thesis*
by (*smt* (*verit*, *ccfv-SIG*) *Collect-cong*)

```
    }
    ultimately have ?thesis by auto
  }
  moreover {
    assume dis: ω − (ω' ∪ ω'') = {} ∧
      ω' − (ω ∪ ω'') = {} ∧
      ω'' − (ω ∪ ω') = {}

    define A where A = (ω ∩ ω'') − ω'
    define B where B = (ω ∩ ω') − ω''
    define C where C = (ω' ∩ ω'') − ω
    define I where I = ω ∩ ω' ∩ ω''

    have f: finite A finite B finite C finite I
      unfolding A-def B-def C-def I-def
      by (meson V ω finite-Diff finite-Int rev-finite-subset)+

    have s: A ⊆ V B ⊆ V C ⊆ V I ⊆ V
      unfolding A-def B-def C-def I-def
      using ω by auto

    have i: I ∩ A = {} I ∩ B = {} I ∩ C = {}
       B ∩ C = {} C ∩ A = {} A ∩ B = {}
      unfolding A-def B-def C-def I-def
      by blast +

    have s1: ω = A ∪ B ∪ I
      unfolding A-def B-def I-def
      using dis by auto
    have sx1: satisfies-xor (xx,bb) ω = b ⟷
       even (card (A ∩ xx)) = even (card (B ∩ xx)) = (b ⟷ satis-
fies-xor(xx,bb) I) for xx bb
      unfolding s1 satisfies-xor.simps Int-Un-distrib2
      apply (subst card-Un-disjoint)
      subgoal using f by auto
      subgoal using f by auto
      subgoal using A-def B-def I-def by blast
      apply (subst card-Un-disjoint)
      subgoal using f by auto
      subgoal using f by auto
      subgoal using A-def B-def I-def by blast
      by auto

    have s2: ω' = B ∪ C ∪ I
      unfolding B-def C-def I-def
      using dis by auto
    have sx2: satisfies-xor (xx,bb) ω' = b' ⟷
       even (card (B ∩ xx)) = even (card (C ∩ xx)) = (b' ⟷ satis-
fies-xor(xx,bb) I) for xx bb
```

unfolding *s2 satisfies-xor.simps Int-Un-distrib2*
apply (*subst card-Un-disjoint*)
subgoal using *f* **by** *auto*
subgoal using *f* **by** *auto*
subgoal using *B-def C-def I-def* **by** *blast*
apply (*subst card-Un-disjoint*)
subgoal using *f* **by** *auto*
subgoal using *f* **by** *auto*
subgoal using *B-def C-def I-def* **by** *blast*
by *auto*

have *s3*: $\omega'' = A \cup C \cup I$
unfolding *A-def C-def I-def*
using *dis* **by** *auto*
have *sx3*: *satisfies-xor* (*xx*,*bb*) $\omega'' = b'' \longleftrightarrow$
even (*card* ($C \cap xx$)) = *even* (*card* ($A \cap xx$)) = ($b'' \longleftrightarrow$ *satisfies-xor*(*xx*,*bb*) *I*) **for** *xx bb*
unfolding *s3 satisfies-xor.simps Int-Un-distrib2*
apply (*subst card-Un-disjoint*)
subgoal using *f* **by** *auto*
subgoal using *f* **by** *auto*
subgoal using *A-def B-def C-def I-def* **by** *blast*
apply (*subst card-Un-disjoint*)
subgoal using *f* **by** *auto*
subgoal using *f* **by** *auto*
subgoal using *A-def B-def C-def I-def* **by** *blast*
by *auto*

have $A = \{\} \wedge B \neq \{\} \wedge C \neq \{\} \vee$
$A \neq \{\} \wedge B = \{\} \wedge C \neq \{\} \vee$
$A \neq \{\} \wedge B \neq \{\} \wedge C = \{\} \vee$
$A \neq \{\} \wedge B \neq \{\} \wedge C \neq \{\}$
by (*metis Un-commute* $\omega(1)$ $\omega(2)$ $\omega(3)$ *s1 s2 s3*)

moreover {
assume *as*: $A = \{\}$ $B \neq \{\}$ $C \neq \{\}$
have *satisfies-xor* (*xx*,*bb*) $\omega = b$
$\wedge$ *satisfies-xor* (*xx*,*bb*) $\omega' = b'$
$\wedge$ *satisfies-xor* (*xx*,*bb*) $\omega'' = b'' \longleftrightarrow$
(*satisfies-xor* (*xx*, *bb*) *I* =
odd (*of-bool b* + *of-bool b'* + *of-bool b''*) $\wedge$
(*even* (*card* ($B \cap xx$)) = ($b' = b''$) $\wedge$
even (*card* ($C \cap xx$)) = ($b = b'$))) **for** *xx bb*
unfolding *sx1 sx2 sx3*
apply(*subst split-boolean-eq*)
using *as* **by** *simp*
then have $*$: {*c*. *satisfies-xor c* $\omega = b$
$\wedge$ *satisfies-xor c* $\omega' = b'$
$\wedge$ *satisfies-xor c* $\omega'' = b''$} =

```
  {c. satisfies-xor c I =
   odd (of-bool b + of-bool b' + of-bool b'') ∧
   even (card (B ∩ fst c)) = (b' = b'') ∧
   even (card (C ∩ fst c)) = (b = b')}
    by (smt (verit,best) Collect-cong prod.collapse)
  have ?thesis
    apply (subst ∗)
    apply (intro three-disjoint-prob-random-xor-nonempty)
    using as s i V by auto
}

moreover {
  assume as: A ≠ {} B ≠ {} C = {}
  have satisfies-xor (xx,bb) ω'' = b''
    ∧ satisfies-xor (xx,bb) ω = b
    ∧ satisfies-xor (xx,bb) ω' = b' ⟷
  (satisfies-xor (xx, bb) I =
   odd (of-bool b'' + of-bool b + of-bool b') ∧
   (even (card (A ∩ xx)) = (b = b') ∧
    even (card (B ∩ xx)) = (b'' = b))) for xx bb
    unfolding sx1 sx2 sx3
    apply(subst split-boolean-eq)
    using as by simp
  then have ∗: {c. satisfies-xor c ω = b
    ∧ satisfies-xor c ω' = b'
    ∧ satisfies-xor c ω'' = b''} =
  {c. satisfies-xor c I =
   odd (of-bool b'' + of-bool b + of-bool b') ∧
   (even (card (A ∩ fst c)) = (b = b') ∧
    even (card (B ∩ fst c)) = (b'' = b))}
    by (smt (verit,best) Collect-cong prod.collapse)
  have ?thesis
    apply (subst ∗)
    apply (intro three-disjoint-prob-random-xor-nonempty)
    using as s i V by auto
}

moreover {
  assume as: A ≠ {} B = {} C ≠ {}
  have satisfies-xor (xx,bb) ω' = b'
    ∧ satisfies-xor (xx,bb) ω'' = b''
    ∧ satisfies-xor (xx,bb) ω = b ⟷
  (satisfies-xor (xx, bb) I =
   odd (of-bool b' + of-bool b'' + of-bool b) ∧
   (even (card (C ∩ xx)) = (b'' = b) ∧
    even (card (A ∩ xx)) = (b' = b''))) for xx bb
    unfolding sx1 sx2 sx3
    apply(subst split-boolean-eq)
    using as by simp
```

```
  then have ∗: {c. satisfies-xor c ω = b
    ∧ satisfies-xor c ω' = b'
    ∧ satisfies-xor c ω'' = b''} =
  {c. satisfies-xor c I =
   odd (of-bool b' + of-bool b'' + of-bool b) ∧
   (even (card (C ∩ fst c)) = (b'' = b) ∧
    even (card (A ∩ fst c)) = (b' = b''))}
    by (smt (verit,best) Collect-cong prod.collapse)
  have ?thesis
    apply (subst ∗)
    apply (intro three-disjoint-prob-random-xor-nonempty)
    using as s i V by auto
}

moreover {
  assume as: A ≠ {} B ≠ {} C ≠ {}
  have 1: satisfies-xor (xx,bb) ω = b
    ∧ satisfies-xor (xx,bb) ω' = b'
    ∧ satisfies-xor (xx,bb) ω'' = b'' ⟷
  (satisfies-xor (xx, bb) I =
    odd (of-bool b + of-bool b' + of-bool b'') ∧
    even (card (A ∩ xx)) = True ∧
    even (card (B ∩ xx)) = (b' = b'') ∧
    even (card (C ∩ xx)) = (b = b') ∨
   satisfies-xor (xx, bb) I =
    odd (of-bool b + of-bool b' + of-bool b'') ∧
    even (card (A ∩ xx)) = False ∧
    even (card (B ∩ xx)) = (b' ≠ b'') ∧
    even (card (C ∩ xx)) = (b ≠ b')) for xx bb
    unfolding sx1 sx2 sx3
    apply(subst split-boolean-eq)
    by auto
  have 2: satisfies-xor c ω = b
    ∧ satisfies-xor c ω' = b'
    ∧ satisfies-xor c ω'' = b'' ⟷
  (satisfies-xor c I =
    odd (of-bool b + of-bool b' + of-bool b'') ∧
    even (card (A ∩ fst c)) = True ∧
    even (card (B ∩ fst c)) = (b' = b'') ∧
    even (card (C ∩ fst c)) = (b = b') ∨
   satisfies-xor c I =
    odd (of-bool b + of-bool b' + of-bool b'') ∧
    even (card (A ∩ fst c)) = False ∧
    even (card (B ∩ fst c)) = (b' ≠ b'') ∧
    even (card (C ∩ fst c)) = (b ≠ b')) for c
  proof −
    obtain xx bb where c:c = (xx,bb) by fastforce
    show ?thesis unfolding c
      apply (subst 1)
```

```
      by auto
    qed
    have ∗: {c. satisfies-xor c ω = b
      ∧ satisfies-xor c ω' = b'
      ∧ satisfies-xor c ω'' = b''} =
    {c. satisfies-xor c I =
      odd (of-bool b + of-bool b' + of-bool b'') ∧
      even (card (A ∩ fst c)) = True ∧
      even (card (B ∩ fst c)) = (b' = b'') ∧
      even (card (C ∩ fst c)) = (b = b')} ∪
    {c. satisfies-xor c I =
      odd (of-bool b + of-bool b' + of-bool b'') ∧
      even (card (A ∩ fst c)) = False ∧
      even (card (B ∩ fst c)) = (b' ≠ b'') ∧
      even (card (C ∩ fst c)) = (b ≠ b')}
      apply (subst Un-def)
      apply (intro Collect-cong)
      apply (subst 2)
      by simp

    have ∗∗: 1 / 16 +
      measure-pmf.prob (random-xor V)
       {c. satisfies-xor c I =
           odd (of-bool b + of-bool b' +
                of-bool b'') ∧
           even (card (A ∩ fst c)) =
           False ∧
           even (card (B ∩ fst c)) =
           (b' ≠ b'') ∧
           even (card (C ∩ fst c)) =
           (b ≠ b')} =
      1 / 8
      apply (subst four-disjoint-prob-random-xor-nonempty)
      using as s i V by auto
    have ?thesis
      apply (subst ∗)
      apply (subst measure-pmf.finite-measure-Union)
      subgoal by simp
      subgoal by simp
      subgoal by auto
      apply (subst four-disjoint-prob-random-xor-nonempty)
      using as s i V ∗∗ by auto
  }

  ultimately have ?thesis by auto
 }
 ultimately show ?thesis by auto
qed
```

2.2 Independence for repeated XORs

We can lift the previous result to a list of independent sampled XORs.

definition *random-xors* :: *'a set* ⇒ *nat* ⇒
  (*nat* ⇀ *'a set* × *bool*) *pmf*
 where *random-xors V n* =
  Pi-pmf {..<(*n*::*nat*)} *None*
   (λ-. *map-pmf Some* (*random-xor V*))

lemma *random-xors-set*:
 assumes *V*:*finite V*
 shows
  PiE-dflt {..<*n*} *None*
   (*set-pmf* ∘ (λ-. *map-pmf Some* (*random-xor V*))) =
  {*xors*. *dom xors* = {..<*n*} ∧
    ran xors ⊆ (*Pow V*) × *UNIV*} (**is** *?lhs* = *?rhs*)
proof −
 have *?lhs* =
  {*f*. *dom f* = {..<*n*} ∧
    (∀ *x* ∈ {..<*n*}. *f x* ∈ *Some* ' (*Pow V* × *UNIV*))}
  unfolding *PiE-dflt-def o-def set-map-pmf set-pmf-random-xor*[*OF V*]
  by *force*

 also have ... = *?rhs*
  apply (*rule antisym*)
  subgoal
   apply *clarsimp*
   by (*smt* (*z3*) *PowD domI image-iff mem-Collect-eq mem-Sigma-iff option.simps*(*1*) *ran-def subsetD*)
  apply *clarsimp*
   by (*smt* (*verit*, *ccfv-threshold*) *domD image-iff lessThan-iff ranI subsetD*)
 finally show *?thesis* **.**
qed

lemma *random-xors-eq*:
 assumes *V*:*finite V*
 shows*random-xors V n* =
  pmf-of-set
  {*xors*. *dom xors* = {..<*n*} ∧ *ran xors* ⊆ (*Pow V*) × *UNIV*}
proof −
 have *pmf-of-set*
  {*xors*. *dom xors* = {..<*n*} ∧
    ran xors ⊆ (*Pow V*) × *UNIV*} =
  pmf-of-set
   (*PiE-dflt* {..<*n*} *None*

```
      (set-pmf ∘ (λ-. map-pmf Some (random-xor V))))
    unfolding random-xors-set[OF V] by auto
  also have ... =
    Pi-pmf {..<n} None
     (λx. pmf-of-set
           ((set-pmf ∘
             (λ-. map-pmf Some (random-xor V))) x))
    apply (subst Pi-pmf-of-set[symmetric])
    by (auto simp add:set-pmf-random-xor[OF V] V)
  also have ... = random-xors V n
    unfolding random-xors-def o-def set-map-pmf
    apply (subst map-pmf-of-set-inj[symmetric])
    subgoal by (auto simp add:set-pmf-random-xor[OF V] V)
    subgoal by (auto simp add:set-pmf-random-xor[OF V] V)
    subgoal by (auto simp add:set-pmf-random-xor[OF V] V)
    by (metis V random-xor-pmf-of-set set-pmf-random-xor)
  ultimately show ?thesis by auto
qed


definition xor-hash ::
  ('a ⇀ bool) ⇒
   (nat ⇀ ('a set × bool)) ⇒
   (nat ⇀ bool)
  where xor-hash ω xors =
     (map-option
       (λxor. satisfies-xor xor {x. ω x = Some True}) ∘ xors)

lemma finite-map-set-nonempty:
  assumes R ≠ {}
  shows
    {xors.
      dom xors = D ∧ ran xors ⊆ R} ≠ {}
proof −
  obtain r where r ∈ R
    using assms by blast
  then have (λx. if x ∈ D then Some r else None) ∈
    {xors. dom xors = D ∧ ran xors ⊆ R}
    by (auto split:if-splits simp:ran-def)
  thus ?thesis by auto
qed

lemma random-xors-set-pmf:
  assumes V: finite V
  shows
    set-pmf (random-xors V n) =
      {xors. dom xors = {..<n} ∧
        ran xors ⊆ (Pow V) × UNIV}
  unfolding random-xors-eq[OF V]
```

apply (*intro set-pmf-of-set*)
subgoal
apply (*intro finite-map-set-nonempty*)
by *blast*
apply (*intro finite-set-of-finite-maps*)
by (*auto simp add*: *V*)

lemma *finite-random-xors-set-pmf*:
assumes *V*: *finite V*
shows
finite (*set-pmf* (*random-xors V n*))
unfolding *random-xors-set-pmf*[*OF V*]
by (*auto intro*!: *finite-set-of-finite-maps simp add*: *V*)

lemma *map-eq-1*:
assumes *dom f* = *dom g*
assumes ⋀*x*. *x* ∈ *dom f* ⟹ *the* (*f x*) = *the* (*g x*)
shows *f* = *g*
by (*metis assms*(*1*) *assms*(*2*) *domIff map-le-antisym map-le-def option.expand*)

lemma *xor-hash-eq-iff*:
assumes *dom* α = {..<*n*}
shows*xor-hash* ω *x* = α ⟷
(*dom x* = {..<*n*} ∧
(∀ *i*. *i* < *n* ⟶
(∃ *xor*. *x i* = *Some xor* ∧
satisfies-xor xor {*x*. ω *x* = *Some True*} = *the* (α *i*))
))
proof −
have *1*: *xor-hash* ω *x* = α ⟷
(*dom* (*xor-hash* ω *x*) = *dom* α) ∧
(∀ *i* ∈ *dom* α. *the* (*xor-hash* ω *x i*) = *the* (α *i*))
using *map-eq-1* **by** *fastforce*
have *2*: *dom* (*xor-hash* ω *x*) = *dom x*
unfolding *xor-hash-def*
by *auto*
have *3*: ⋀*i*. *i* ∈ *dom x* ⟹
xor-hash ω *x i* = *Some* (*satisfies-xor* (*the* (*x i*)) {*x*. ω *x* = *Some True*})
unfolding *xor-hash-def*
by *fastforce*
show *?thesis*
unfolding *1 assms 2*
using *3*
by (*smt* (*verit*, *best*) *domD lessThan-iff option.sel*)
qed

lemma *xor-hash-eq-PiE-dflt*:

assumes *dom* $\alpha = \{..<n\}$
shows
$\{xors.\ xor\text{-}hash\ \omega\ xors = \alpha\} =$
PiE-dflt $\{..<n\}$ *None*
$(\lambda i.\ Some\ `$
$\{xor.\ satisfies\text{-}xor\ xor\ \{x.\ \omega\ x = Some\ True\} = the\ (\alpha\ i)\}$)
proof −
have $*$: $\bigwedge x\ xa\ a\ b.$
$(\neg\ xa < n \longrightarrow x\ xa = None) \Longrightarrow$
$x\ xa = Some\ (a,\ b) \Longrightarrow xa < n$
by (*metis option.distinct*(*2*))
show *?thesis*
unfolding *PiE-dflt-def*
unfolding *xor-hash-eq-iff*[*OF assms*]
by (*auto intro*: $*$ *simp del*: *satisfies-xor.simps*)
qed

lemma *prob-random-xors-xor-hash*:
assumes *V*: *finite V*
assumes α: *dom* $\alpha = \{..<n\}$
shows
measure-pmf.prob (*random-xors V n*)
$\{xors.\ xor\text{-}hash\ \omega\ xors = \alpha\} = 1\ /\ 2\ \hat{}\ n$
proof −
have *measure-pmf.prob* (*random-xors V n*)
$\{xors.\ xor\text{-}hash\ \omega\ xors = \alpha\} =$
measure-pmf.prob
(*Pi-pmf* $\{..<(n::nat)\}$ *None*
$(\lambda\text{-}.\ map\text{-}pmf\ Some\ (random\text{-}xor\ V)))$
(*PiE-dflt* $\{..<n\}$ *None*
$(\lambda i.\ Some\ `\ \{xor.\ satisfies\text{-}xor\ xor\ \{x.\ \omega\ x = Some\ True\} = the$
$(\alpha\ i)\}))$
unfolding *random-xors-def xor-hash-eq-PiE-dflt*[*OF* α]
by *auto*
also have ... =
$(\prod x<n.\ measure\text{-}pmf.prob\ (random\text{-}xor\ V)$
$(\{xor.$
satisfies-xor xor $\{x.\ \omega\ x = Some\ True\} =$
the $(\alpha\ x)\}))$
by (*subst measure-Pi-pmf-PiE-dflt*)
(*auto simp add*: *inj-vimage-image-eq*)
also have ... = $(\prod x<n.\ 1/2)$
by (*simp add*: *assms*(*1*) *satisfies-random-xor-parity*)
also have ... = $1/\ 2\ \hat{}\ n$
by (*simp add*: *power-one-over*)
finally show *?thesis* **by** *auto*
qed

lemma *PiE-dflt-inter*:

shows *PiE-dflt A dflt B ∩ PiE-dflt A dflt B′ =*
PiE-dflt A dflt (λb. B b ∩ B′ b)
unfolding *PiE-dflt-def*
by *auto*

lemma *random-xors-xor-hash-pair*:
assumes *V*: *finite V*
assumes *α*: *dom α = {..<n}*
assumes *α′*: *dom α′ = {..<n}*
assumes *ω*: *dom ω = V*
assumes *ω′*: *dom ω′ = V*
assumes *neq*: *ω ≠ ω′*
shows
measure-pmf.prob (random-xors V n)
{xors. xor-hash ω xors = α ∧ xor-hash ω′ xors = α′} =
1 / 4 ^ n
proof −
obtain *y* **where** *ω y ≠ ω′ y*
using *neq*
by *blast*
then have *neq*:*{x. ω x = Some True} ≠ {x. ω′ x = Some True}*
by (*smt* (*verit*, *ccfv-threshold*) *assms*(*4*) *assms*(*5*) *domD domIff mem-Collect-eq*)
have *measure-pmf.prob (random-xors V n)*
{xors.
xor-hash ω xors = α ∧ xor-hash ω′ xors = α′} =
measure-pmf.prob (random-xors V n)
({xors. xor-hash ω xors = α} ∩
{xors. xor-hash ω′ xors = α′})
by (*simp add*: *Collect-conj-eq*)
also have ... =
measure-pmf.prob
(Pi-pmf {..<(n::nat)} None
(λ-. map-pmf Some (random-xor V)))
(PiE-dflt {..<n} None
(λi. Some ‘ {xor. satisfies-xor xor {x. ω x = Some True} = the (α i)})
∩
PiE-dflt {..<n} None
(λi. Some ‘ {xor. satisfies-xor xor {x. ω′ x = Some True} = the (α′ i)}))
unfolding *random-xors-def xor-hash-eq-PiE-dflt*[*OF α*] *xor-hash-eq-PiE-dflt*[*OF α′*]
by *auto*
also have ... =
measure-pmf.prob
(Pi-pmf {..<(n::nat)} None
(λ-. map-pmf Some (random-xor V)))
(PiE-dflt {..<n} None

```
      (λi.
      Some ‘ {xor.
        satisfies-xor xor {x. ω x = Some True} = the (α i) ∧
        satisfies-xor xor {x. ω' x = Some True} = the (α' i)}))
    unfolding PiE-dflt-inter
    apply (subst image-Int[symmetric])
    by (auto simp add: Collect-conj-eq)

  also have ... =
    (∏ x<n. measure-pmf.prob (random-xor V)
      ({xor.
        satisfies-xor xor {x. ω x = Some True} = the (α x) ∧
        satisfies-xor xor {x. ω' x = Some True} = the (α' x)}))
    by (subst measure-Pi-pmf-PiE-dflt)
     (auto simp add: inj-vimage-image-eq)
  also have ... = (∏ x<n. 1/4)
    apply (subst pair-satisfies-random-xor-parity)
    using assms neq by auto
  also have ... = 1/ 4 ^ n
    by (simp add: power-one-over)
  finally show ?thesis by auto
qed

lemma random-xors-xor-hash-three:
  assumes V: finite V
  assumes α: dom α = {..<n}
  assumes α': dom α' = {..<n}
  assumes α'': dom α'' = {..<n}
  assumes ω: dom ω = V
  assumes ω': dom ω' = V
  assumes ω': dom ω'' = V
  assumes neq: ω ≠ ω' ω' ≠ ω'' ω'' ≠ ω
  shows
  measure-pmf.prob (random-xors V n)
    {xors.
      xor-hash ω xors = α
      ∧ xor-hash ω' xors = α'
      ∧ xor-hash ω'' xors = α''} =
    1 / 8 ^ n
proof −
  obtain x y z where ω x ≠ ω' x ω' y ≠ ω'' y ω'' z ≠ ω z
    using neq
    by blast
  then have neq:
    {x. ω x = Some True} ≠ {x. ω' x = Some True}
    {x. ω' x = Some True} ≠ {x. ω'' x = Some True}
    {x. ω'' x = Some True} ≠ {x. ω x = Some True}
   by (smt (verit, ccfv-threshold) assms domD domIff mem-Collect-eq)+
  have measure-pmf.prob (random-xors V n)
```

```
    {xors.
     xor-hash ω xors = α ∧ xor-hash ω' xors = α' ∧ xor-hash ω'' xors
= α''} =
    measure-pmf.prob (random-xors V n)
      ({xors. xor-hash ω xors = α} ∩
      {xors. xor-hash ω' xors = α'} ∩
      {xors. xor-hash ω'' xors = α''})
    by (simp add: measure-pmf.measure-pmf-eq)
  moreover have ... =
    measure-pmf.prob
    (Pi-pmf {..<(n::nat)} None
      (λ-. map-pmf Some (random-xor V)))
    (PiE-dflt {..<n} None
      (λi. Some ` {xor. satisfies-xor xor {x. ω x = Some True} = the
(α i)})
    ∩
    PiE-dflt {..<n} None
      (λi. Some ` {xor. satisfies-xor xor {x. ω' x = Some True} = the
(α' i)})
    ∩
    PiE-dflt {..<n} None
      (λi. Some ` {xor. satisfies-xor xor {x. ω'' x = Some True} = the
(α'' i)}))
   unfolding random-xors-def xor-hash-eq-PiE-dflt[OF α] xor-hash-eq-PiE-dflt[OF
α'] xor-hash-eq-PiE-dflt[OF α'']
    by auto
  moreover have ... =
    measure-pmf.prob
    (Pi-pmf {..<(n::nat)} None
      (λ-. map-pmf Some (random-xor V)))
    (PiE-dflt {..<n} None
      (λi.
      Some ` {xor.
        satisfies-xor xor {x. ω x = Some True} = the (α i) ∧
        satisfies-xor xor {x. ω' x = Some True} = the (α' i) ∧
        satisfies-xor xor {x. ω'' x = Some True} = the (α'' i)}))

    unfolding PiE-dflt-inter
    apply (subst image-Int[symmetric])
    subgoal by simp
    apply (intro arg-cong[where f=measure-pmf.prob
     (Pi-pmf {..<n} None
       (λ-. map-pmf Some (random-xor V)))])
    apply (intro arg-cong[where f=PiE-dflt {..<n} None])
    by auto

  moreover have ... =
    (∏ x<n. measure-pmf.prob (random-xor V)
      ({xor.
```

```
      satisfies-xor xor {x. ω x = Some True} = the (α x) ∧
      satisfies-xor xor {x. ω' x = Some True} = the (α' x)∧
      satisfies-xor xor {x. ω'' x = Some True} = the (α'' x)}))
   apply (subst measure-Pi-pmf-PiE-dflt)
   by (auto simp add: inj-vimage-image-eq)
 moreover have ... = (∏ x<n. 1/8)
   apply (subst three-satisfies-random-xor-parity)
   subgoal using assms neq by clarsimp
   subgoal using assms neq by clarsimp
   subgoal using assms neq by clarsimp
   subgoal using assms neq by clarsimp
   subgoal using assms(5) by blast
   subgoal using assms(6) by blast
   subgoal using assms(7) by blast
   by auto
 moreover have ... = 1/ 8 ^ n
   by (simp add: power-one-over)
 ultimately show ?thesis by auto
qed

end
```

3 Random XOR hash family

This section defines a hash family based on random XORs and proves that this hash family is 3-universal.

```
theory RandomXORHashFamily imports
  RandomXOR
begin

lemma finite-dom:
  assumes finite V
  shows finite {w :: 'a ⇀ bool. dom w = V}
proof −
  have ∗: {w :: 'a ⇀ bool. dom w = V} =
    {w. dom w = V ∧ ran w ⊆ {True,False}}
    by auto
  show ?thesis unfolding ∗
    apply (intro finite-set-of-finite-maps)
    using assms by auto
qed

lemma xor-hash-eq-dom:
  assumes xor-hash ω xors = α
  shows dom xors = dom α
  using assms unfolding xor-hash-def
  by auto
```

lemma *prob-random-xors-xor-hash-indicat-real*:
assumes *V*: *finite V*
shows
measure-pmf.prob (*random-xors V n*)
{*xors*. *xor-hash ω xors* = *α*} =
indicat-real {*α*::*nat* ⇀ *bool*. *dom α* = {*0*..<*n*}} *α* /
real (*card* {*α*::*nat* ⇀ *bool*. *dom α* = {*0*..<*n*}})
proof −
have ∗: {*α*::*nat* ⇀ *bool*. *dom α* = {*0*..<*n*}} =
{*α*. *dom α* = {*0*..<*n*} ∧ *ran α* ⊆ {*True*, *False*}}
by *auto*
have ∗∗: *card* {*α*::*nat* ⇀ *bool*. *dom α* = {*0*..<*n*}} = *2*^*n*
unfolding ∗
apply (*subst card-dom-ran*)
by (*auto simp add*: *numerals*(*2*))
have *dom α* = {..<*n*} ∨ *dom α* ≠ {..<*n*}
by *auto*
moreover {
assume *dom α* = {..<*n*}
from *prob-random-xors-xor-hash*[*OF V this*]
have *?thesis*
unfolding ∗∗
by (*simp add*: ‹*dom α* = {..<*n*}› *atLeast0LessThan*)
}
moreover {
assume ∗:*dom α* ≠ {..<*n*}
then have *x* ∈ *set-pmf* (*random-xors V n*) ⟹
α ≠ *xor-hash ω x* **for** *x*
by (*metis* (*mono-tags*, *lifting*) *V mem-Collect-eq random-xors-set-pmf xor-hash-eq-dom*)
then have *measure-pmf.prob* (*random-xors V n*)
{*xors*. *xor-hash ω xors* = *α*} = *0*
apply (*intro measure-pmf.measure-exclude*[**where** *A* = *set-pmf* ((*random-xors V n*))])
by (*auto simp add*: *Sigma-Algebra.measure-def emeasure-pmf xor-hash-eq-dom*)
then have *?thesis*
by (*simp add*: ∗ *atLeast0LessThan*)
}
ultimately show *?thesis*
by *auto*
qed

lemma *xor-hash-family-uniform*:
assumes *V*: *finite V*
assumes *dom ω* = *V*
shows *prob-space.uniform-on*
(*random-xors V n*)
(*xor-hash i*) {*α*. *dom α* = {*0*..<*n*}}

apply (*intro measure-pmf.uniform-onI*[**where** p = *random-xors* V n])
subgoal by *clarsimp*
subgoal using *finite-dom* **by** *blast*
using *prob-random-xors-xor-hash-indicat-real*[*OF* V]
by (*auto intro*!: *exI*[**where** x = (λi. *if* $i < n$ *then Some True else None*)] *split*:*if-splits*)

lemma *random-xors-xor-hash-pair-indicat*:
assumes V: *finite* V
assumes ω: *dom* ω = V
assumes ω': *dom* ω' = V
assumes *neq*: $\omega \neq \omega'$
shows
measure-pmf.prob (*random-xors* V n)
{*xors*.
xor-hash ω *xors* = α $\wedge$ *xor-hash* ω' *xors* = α'} =
(*measure-pmf.prob* (*random-xors* V n)
{*xors*.
xor-hash ω *xors* = α} $*$
measure-pmf.prob (*random-xors* V n)
{*xors*.
xor-hash ω' *xors* = α'})
proof −
have *dom* α = {..<n} $\wedge$ *dom* α' = {..<n} $\vee$
¬(*dom* α = {..<n} $\wedge$ *dom* α' = {..<n}) **by** *auto*
moreover {
assume $*$: *dom* α = {..<n} *dom* α' = {..<n}
have *measure-pmf.prob* (*random-xors* V n)
{*xors*.
xor-hash ω *xors* = α $\wedge$ *xor-hash* ω' *xors* = α'} = *1* / *4* ^ n
by (*simp add*: $*$(*1*) $*$(*2*) *assms*(*1*) *assms*(*2*) *assms*(*3*) *assms*(*4*) *random-xors-xor-hash-pair*)
moreover have
measure-pmf.prob (*random-xors* V n)
{*xors*. *xor-hash* ω *xors* = α} = *1*/*2*^n
by (*simp add*: $*$(*1*) *assms*(*1*) *prob-random-xors-xor-hash*)
moreover have
measure-pmf.prob (*random-xors* V n)
{*xors*. *xor-hash* ω' *xors* = α'} = *1*/*2*^n
by (*simp add*: $*$(*2*) *assms*(*1*) *prob-random-xors-xor-hash*)
ultimately have *?thesis*
by (*metis* (*full-types*) *Groups.mult-ac*(*2*) *four-x-squared power2-eq-square power-mult power-one-over verit-prod-simplify*(*2*))
}
moreover {
assume $*$: *dom* $\alpha \neq$ {..<n} $\vee$ *dom* $\alpha' \neq$ {..<n}
then have $**$: $x \in$ *set-pmf* (*random-xors* V n) $\Longrightarrow$
α = *xor-hash* ω x $\Longrightarrow$

$\alpha' = \textit{xor-hash}\ \omega'\ x \Longrightarrow \textit{False}$ **for** x
by (*metis* (*mono-tags*, *lifting*) *CollectD assms*(*1*) *random-xors-set-pmf xor-hash-eq-dom*)
have *measure-pmf.prob* (*random-xors V n*)
{*xors*.
xor-hash ω xors = *α*} = *0* ∨
measure-pmf.prob (*random-xors V n*)
{*xors*.
xor-hash ω′ xors = *α′*} = *0*
unfolding *prob-random-xors-xor-hash-indicat-real*[*OF V*]
by (*metis* (*full-types*) ∗ *atLeast0LessThan div-0 indicator-simps*(*2*) *mem-Collect-eq*)
moreover have
measure-pmf.prob (*random-xors V n*)
{*xors*.
xor-hash ω xors = *α* ∧ *xor-hash ω′ xors* = *α′*} = *0*
apply (*intro measure-pmf.measure-exclude*[**where** *A* = *set-pmf* ((*random-xors V n*))])
using ∗∗ **by** (*auto simp add*: *Sigma-Algebra.measure-def emeasure-pmf*)
ultimately have *?thesis* **by** *auto*
}
ultimately show *?thesis* **by** *auto*
qed

lemma *prod-3-expand*:
assumes *a* ≠ *b b* ≠ *c c* ≠ *a*
shows(∏ *ω*∈{*a*, *b*, *c*}. *f ω*) = *f a* ∗ (*f b* ∗ *f c*)
using *assms* **by** *auto*

lemma *random-xors-xor-hash-three-indicat*:
assumes *V*: *finite V*
assumes *ω*: *dom ω* = *V*
assumes *ω′*: *dom ω′* = *V*
assumes *ω″*: *dom ω″* = *V*
assumes *neq*: *ω* ≠ *ω′ ω′* ≠ *ω″ ω″* ≠ *ω*
shows
measure-pmf.prob (*random-xors V n*)
{*xors*.
xor-hash ω xors = *α*
∧ *xor-hash ω′ xors* = *α′*
∧ *xor-hash ω″ xors* = *α″*} =
(*measure-pmf.prob* (*random-xors V n*)
{*xors*.
xor-hash ω xors = *α*} ∗
measure-pmf.prob (*random-xors V n*)
{*xors*.
xor-hash ω′ xors = *α′*} ∗
measure-pmf.prob (*random-xors V n*)

```
    {xors.
      xor-hash ω'' xors = α''})
proof −
  have dom α = {..<n} ∧ dom α' = {..<n} ∧ dom α'' = {..<n} ∨
    ¬(dom α = {..<n} ∧ dom α' = {..<n} ∧ dom α'' = {..<n}) by
auto
  moreover {
    assume ∗: dom α = {..<n} dom α' = {..<n} dom α'' = {..<n}
    have 1:measure-pmf.prob (random-xors V n)
     {xors.
      xor-hash ω xors = α ∧
      xor-hash ω' xors = α' ∧
      xor-hash ω'' xors = α''} = 1 / 8 ^n
      apply (intro random-xors-xor-hash-three)
      using V ∗ ω ω' ω'' neq by auto
    have 2:
    measure-pmf.prob (random-xors V n)
      {xors.  xor-hash ω xors = α} = 1/2^n
      by (simp add: ∗(1) assms(1) prob-random-xors-xor-hash)
    have 3:
    measure-pmf.prob (random-xors V n)
      {xors.  xor-hash ω' xors = α'} = 1/2^n
      by (simp add: ∗(2) assms(1) prob-random-xors-xor-hash)
    have 4:
    measure-pmf.prob (random-xors V n)
      {xors.  xor-hash ω'' xors = α''} = 1/2^n
      by (simp add: ∗(3) assms(1) prob-random-xors-xor-hash)
    have ?thesis
      unfolding 1 2 3 4
    by (metis (mono-tags, opaque-lifting) arith-simps(11) arith-simps(12)
arith-simps(58) divide-divide-eq-left mult.right-neutral power-mult-distrib
times-divide-eq-right)
  }
  moreover {
     assume ∗: dom α ≠ {..<n} ∨ dom α' ≠ {..<n} ∨ dom α'' ≠
{..<n}
    then have ∗∗: x ∈ set-pmf (random-xors V n) ⟹
        α = xor-hash ω x ⟹
        α' = xor-hash ω' x ⟹
        α'' = xor-hash ω'' x ⟹ False for x
    by (metis (mono-tags, lifting) CollectD assms(1) random-xors-set-pmf
xor-hash-eq-dom)
    have measure-pmf.prob (random-xors V n)
    {xors.
      xor-hash ω xors = α} = 0 ∨
     measure-pmf.prob (random-xors V n)
      {xors.
        xor-hash ω' xors = α'} = 0 ∨
     measure-pmf.prob (random-xors V n)
```

```
    {xors.
      xor-hash ω'' xors = α''} = 0
    unfolding prob-random-xors-xor-hash-indicat-real[OF V]
   by (metis (full-types) * atLeast0LessThan div-0 indicator-simps(2)
mem-Collect-eq)
  moreover have
  measure-pmf.prob (random-xors V n)
  {xors.
   xor-hash ω xors = α ∧ xor-hash ω' xors = α' ∧ xor-hash ω'' xors
= α''} = 0
    apply (intro measure-pmf.measure-exclude[where A = set-pmf
((random-xors V n))])
    using ** by (auto simp add: Sigma-Algebra.measure-def emea-
sure-pmf)
  ultimately have ?thesis by auto
 }
 ultimately show ?thesis
  by fastforce
qed

lemma xor-hash-3-indep:
 assumes V: finite V
 assumes J: card J ≤ 3 J ⊆ {α. dom α = V}
 shows
  measure-pmf.prob (random-xors V n)
   {xors. ∀ω∈J. xor-hash ω xors = f ω} =
   (∏ω∈J.
     measure-pmf.prob (random-xors V n)
      {xors. xor-hash ω xors = f ω})
proof −
 have card J = 0 ∨ card J = 1 ∨ card J = 2 ∨ card J = 3
  using assms by auto
 moreover {
  assume card J = 0
  then have J = {}
  by (meson assms(1) assms(3) card-eq-0-iff finite-dom finite-subset)
  then have ?thesis
   by clarsimp
 }
 moreover {
  assume card J = 1
  then obtain x where J = {x}
   using card-1-singletonE by blast
  then have ?thesis
   by auto
 }
 moreover {
  assume card J = 2
  then obtain ω ω' where J:J = {ω, ω'} and
```

```
    ω: ω ≠ ω' dom ω = V dom ω' = V
    unfolding card-2-iff
    using J
    by force
  have ?thesis unfolding J
    by (auto simp add: random-xors-xor-hash-pair-indicat V ω)
 }
 moreover {
  assume card J = 3
  then obtain ω ω' ω'' where J:J = {ω, ω', ω''} and
    ω: ω ≠ ω' ω' ≠ ω'' ω'' ≠ ω
      dom ω = V dom ω' = V dom ω'' = V
    unfolding card-3-iff
    using J
    by force
  have ?thesis unfolding J
      by (auto simp add: random-xors-xor-hash-three-indicat V ω
prod-3-expand[OF ω(1−3)])
 }
 ultimately show ?thesis by auto
qed

lemma xor-hash-3-wise-indep:
 assumes finite V
 shows prob-space.k-wise-indep-vars
   (random-xors V n) 3
   (λ-. Universal-Hash-Families-More-Independent-Families.discrete)
xor-hash
   {α. dom α = V}
 apply (subst prob-space.k-wise-indep-vars-def)
 by (auto intro!: measure-pmf.indep-vars-pmf xor-hash-3-indep simp
add: measure-pmf.prob-space-axioms assms card-mono dual-order.trans)

theorem xor-hash-family-3-universal:
 assumes finite V
 showsprob-space.k-universal
   (random-xors V n) 3 xor-hash
   {α::'a ⇀ bool. dom α = V}
   {α::nat ⇀ bool. dom α = {0..<n}}
 apply (subst prob-space.k-universal-def)
 subgoal by (clarsimp simp add: measure-pmf.prob-space-axioms )
  using xor-hash-3-wise-indep assms xor-hash-family-uniform assms
by blast

corollary xor-hash-family-2-universal:
 assumes finite V
 showsprob-space.k-universal
   (random-xors V n) 2 xor-hash
   {α::'a ⇀ bool. dom α = V}
```

$\{\alpha::nat \rightharpoonup bool.\ dom\ \alpha = \{0..<n\}\}$
using *assms*
by (*auto intro*!: *prob-space.k-universal-mono*[*OF - - xor-hash-family-3-universal*] *measure-pmf.prob-space-axioms*)

end

4 ApproxMCCore definitions

This section defines the ApproxMCCore locale and various failure events to be used in its probabilistic analysis. The definitions closely follow Section 4.2 of Chakraborty et al. [1]. Some non-probabilistic properties of the events are proved, most notably, the event inclusions of Lemma 3 [1]. Note that "events" here refer to subsets of hash functions.

theory *ApproxMCCore* **imports**
ApproxMCPreliminaries
begin

type-synonym *'a assg* = *'a* $\rightharpoonup$ *bool*

definition *restr* :: *'a set* $\Rightarrow$ (*'a* $\Rightarrow$ *bool*) $\Rightarrow$ *'a assg*
where *restr S w* = ($\lambda x.$ *if* $x \in S$ *then Some* (*w x*) *else None*)

lemma *restrict-eq-mono*:
assumes $x \subseteq y$
assumes *f* |` *y* = *g* |` *y*
shows *f* |` *x* = *g* |` *x*
using *assms*
by (*metis Map.restrict-restrict inf.absorb-iff2*)

definition *proj* :: *'a set* $\Rightarrow$ (*'a* $\Rightarrow$ *bool*) *set* $\Rightarrow$ *'a assg set*
where *proj S W* = *restr S* ` *W*

lemma *card-proj*:
assumes *finite S*
shows *finite* (*proj S W*) *card* (*proj S W*) $\leq$ *2* $\hat{}$ *card S*
proof −
have $*$: *proj S W* $\subseteq$ {*w. dom w* = *S*}
unfolding *proj-def restr-def*
by (*auto split*: *if-splits*)
also have *1*: {*w. dom w* = *S*} = {*w. dom w* = *S* $\wedge$ *ran w* $\subseteq$ {*True*,*False*}}
by *auto*

have *f*: *finite* {*w*. *dom w* = *S* ∧ *ran w* ⊆ {*True*,*False*}}
by (*simp add*: *assms finite-set-of-finite-maps*)
thus *finite* (*proj S W*)
using ∗ *1*
by (*metis finite-subset*)

have *2*:*card* {*w*. *dom w* = *S* ∧ *ran w* ⊆ {*True*,*False*}} = (*card* {*True*,*False*}) ^ *card S*
apply (*intro card-dom-ran*)
using *assms* **by** *auto*

show *card* (*proj S W*) ≤ *2* ^ *card S*
using ∗ *1 2*
by (*metis* (*no-types*, *lifting*) *f card.empty card-insert-disjoint card-mono finite.emptyI finite.insertI insert-absorb insert-not-empty numeral-2-eq-2 singleton-insert-inj-eq*)
qed

lemma *proj-mono*:
assumes *x* ⊆ *y*
shows *proj w x* ⊆ *proj w y*
unfolding *proj-def*
using *assms* **by** *blast*

definition *aslice* :: *nat* ⇒ *nat assg* ⇒ *nat assg*
where *aslice i a* = *a* |‘ {..<*i*}

lemma *aslice-eq*:
assumes *i* ≥ *n*
assumes *dom a* = {..<*n*}
shows *aslice i a* = *aslice n a*
using *assms*
unfolding *aslice-def restrict-map-def dom-def*
by *fastforce*

definition *hslice* :: *nat* ⇒
(′*a assg* ⇒ *nat assg*) ⇒ (′*a assg* ⇒ *nat assg*)
where *hslice i h* = *aslice i* ∘ *h*

locale *ApproxMCCore* =
fixes *W* :: (′*a* ⇒ *bool*) *set*
fixes *S* :: ′*a set*
fixes ε :: *real*
fixes α :: *nat assg*
fixes *thresh* :: *nat*
assumes α: *dom* α = {*0*..<*card S* − *1*}

assumes ε: $\varepsilon > 0$
assumes *thresh*:
$4 < thresh$
$thresh \leq card\ (proj\ S\ W)$
assumes S: *finite* S
begin

lemma *finite-proj-S*:
shows *finite* (*proj* S W)
using S **by** (*auto intro*!: *card-proj*)

definition μ :: *nat* $\Rightarrow$ *real*
where $\mu\ i = card\ (proj\ S\ W)\ /\ 2\ \hat{}\ i$

definition *card-slice* ::
('*a assg* $\Rightarrow$ *nat assg*) $\Rightarrow$
nat $\Rightarrow$ *nat*
where *card-slice* $h\ i =$
card (*proj* S $W \cap \{w.\ hslice\ i\ h\ w = aslice\ i\ \alpha\}$)

lemma *card-slice-anti-mono*:
assumes $i \leq j$
shows *card-slice* $h\ j \leq$ *card-slice* $h\ i$
proof −
have $*$: $\{..<i\} \subseteq \{..<j\}$ **using** *assms* **by** *auto*
have $\{w.\ hslice\ j\ h\ w = aslice\ j\ \alpha\}$
$\subseteq \{w.\ hslice\ i\ h\ w = aslice\ i\ \alpha\}$
by (*auto intro*: *restrict-eq-mono*[*OF* $*$] *simp add*: *hslice-def aslice-def*)
thus *?thesis*
unfolding *card-slice-def*
apply (*intro card-mono*)
subgoal using *finite-proj-S* **by** *blast*
by (*auto intro*!: *proj-mono*)
qed

lemma *hslice-eq*:
assumes $n \leq i$
assumes $\bigwedge w.\ dom\ (h\ w) = \{..<n\}$
shows *hslice* $i\ h =$ *hslice* $n\ h$
using *assms aslice-eq*
unfolding *hslice-def* **by** *auto*

lemma *card-slice-lim*:
assumes *card* $S - 1 \leq i$
assumes $\bigwedge w.\ dom\ (h\ w) = \{..<(card\ S - 1)\}$
shows *card-slice* $h\ i =$ *card-slice* h (*card* $S - 1$)
unfolding *card-slice-def*
apply(*subst aslice-eq*[*OF assms*(*1*)])

subgoal using α **by** *auto*
apply(*subst hslice-eq*[*OF assms*(*1*)])
using *assms* **by** *auto*

definition $T :: nat \Rightarrow$
$('a\ assg \Rightarrow nat\ assg)\ set$
where $T\ i = \{h.\ card\text{-}slice\ h\ i < thresh\}$

lemma *T-mono*:
assumes $i \leq j$
shows $T\ i \subseteq T\ j$
unfolding *T-def*
using *card-slice-anti-mono*[*OF assms*]
dual-order.strict-trans2
of-nat-mono
by *blast*

lemma μ*-anti-mono*:
assumes $i \leq j$
shows $\mu\ i \geq \mu\ j$
proof −
have $2\hat{}\ i \leq (2::real)\ \hat{}\ j$
by (*simp add*: *assms*)
then show *?thesis* **unfolding** μ*-def*
by (*simp add*: *frac-le*)
qed

lemma *card-proj-witnesses*:
card (*proj S W*) > *0*
using *thresh* **by** *linarith*

lemma μ*-strict-anti-mono*:
assumes $i < j$
shows $\mu\ i > \mu\ j$
proof −
have $2\hat{}\ i < (2::real)\ \hat{}\ j$
by (*simp add*: *assms*)
then show *?thesis* **unfolding** μ*-def*
using *card-proj-witnesses*
by (*simp add*: *frac-less2*)
qed

lemma μ*-gt-zero*:
shows $\mu\ i > 0$
unfolding μ*-def*
using *card-proj-witnesses*
by *auto*

```
definition L :: nat ⇒
  ('a assg ⇒ nat assg) set
  where
    L i =
    {h. real (card-slice h i) < μ i / (1 + ε)}

definition U :: nat ⇒
  ('a assg ⇒ nat assg) set
  where
    U i =
    {h. real (card-slice h i) ≥ μ i * (1 + ε / (1 + ε))}


definition approxcore ::
  ('a assg ⇒ nat assg) ⇒
  nat × nat
  where
    approxcore h =
    (case List.find
      (λi. h ∈ T i) [1..<card S] of
      None ⇒ (2 ^ card S, 1)
    | Some m ⇒
      (2 ^ m, card-slice h m))


definition approxcore-fail ::
  ('a assg ⇒ nat assg) set
  where approxcore-fail =
    {h.
      let (cells,sols) = approxcore h in
      cells * sols ∉
      { card (proj S W) / (1 + ε) ..
        (1 + ε::real) * card (proj S W)}
    }


lemma T0-empty:
  shows T 0 = {}
  unfolding T-def card-slice-def
    hslice-def aslice-def
  using thresh(2) by auto

lemma L0-empty:
  shows L 0 = {}
proof −
  have 0 < ε ⟹
    real (card (proj S W))
    < real (card (proj S W)) / (1 + ε) ⟹
    False
```

by (*smt* (*z3*) *card-proj-witnesses divide-minus1 frac-less2 nonzero-minus-divide-right of-nat-0-less-iff*)
thus *?thesis*
unfolding *L-def card-slice-def hslice-def aslice-def* μ*-def*
using ε **by** *clarsimp*
qed

lemma *U0-empty*:
shows $U\ 0 = \{\}$
proof −
have $*$: $(1 + \varepsilon\ /\ (1 + \varepsilon)) > 1$
using ε **by** *auto*
have $**$: $U\ 0 = \{\}$
unfolding *U-def card-slice-def hslice-def aslice-def* μ*-def*
using $*$
by (*simp add*: *card-proj-witnesses*)
thus *?thesis* **using** $**$ **by** *auto*
qed

lemma *real-divide-pos-left*:
assumes $(0::real) < a$
assumes $a * b < c$
shows $b < c\ /\ a$
using *assms*
by (*simp add*: *mult.commute mult-imp-less-div-pos*)

lemma *real-divide-pos-right*:
assumes $a > (0::real)$
assumes $b < a * c$
shows $b\ /\ a < c$
using *assms*
by (*simp add*: *mult.commute mult-imp-div-pos-less*)

lemma *failure-imp*:
shows *approxcore-fail* $\subseteq$
$(\bigcup i{\in}\{1..{<}card\ S\}.$
$(T\ i\ -\ T\ (i{-}1)) \cap (L\ i \cup U\ i)) \cup$
$-T\ (card\ S\ -\ 1)$
proof *standard*
fix *h*
assume $h \in$ *approxcore-fail*
then obtain *cells sols* **where**
h: *approxcore h* = (*cells*, *sols*)
cells $*$ *sols* $\notin$
$\{\ card\ (proj\ S\ W)\ /\ (1 + \varepsilon)\ ..$
$(1 + \varepsilon::real) * card\ (proj\ S\ W)\}$ (**is** - $\notin \{?lower..?upper\}$)

unfolding *approxcore-fail-def*
by *auto*

have *List.find* ($\lambda i.\ h \in T\ i$) [*1*..<*card S*] = *None* ∨
List.find ($\lambda i.\ h \in T\ i$) [*1*..<*card S*] ≠ *None* **by** *auto*
moreover {
assume *List.find* ($\lambda i.\ h \in T\ i$) [*1*..<*card S*] = *None*
then have $h \notin T\ (card\ S - 1)$
unfolding *find-None-iff*
by (*metis T0-empty atLeastLessThan-iff diff-is-0-eq' diff-less empty-iff gr-zeroI leI less-one not-less-zero set-upt*)
}
moreover {
assume *List.find* ($\lambda i.\ h \in T\ i$) [*1*..<*card S*] ≠ *None*
then obtain *m* **where**
findm: *List.find* ($\lambda i.\ h \in T\ i$) [*1*..<*card S*] = *Some m* **by** *auto*
then have
m: $1 \le m\ m < card\ S$
$h \in T\ m$
$\forall i.\ 1 \le i \wedge i < m \longrightarrow h \notin T\ i$
unfolding *find-Some-iff*
using *less-Suc-eq-0-disj* **by** *auto*

then have *1*: $h \notin T\ (m - 1)$
by (*metis T0-empty bot-nat-0.not-eq-extremum diff-is-0-eq diff-less empty-iff less-one*)

have $2 \hat{} m * card\text{-}slice\ h\ m < ?lower \vee$
$2 \hat{} m * card\text{-}slice\ h\ m > ?upper$
using *h* **unfolding** *approxcore-def findm* **by** *auto*
moreover {
assume $2 \hat{} m * card\text{-}slice\ h\ m < ?lower$
then have $card\text{-}slice\ h\ m < ?lower\ /\ 2 \hat{} m$
using *real-divide-pos-left*
by (*metis numeral-power-eq-of-nat-cancel-iff of-nat-mult zero-less-numeral zero-less-power*)

then have $h \in L\ m$ **unfolding** *L-def*
by (*simp add*: *μ-def mult.commute*)
}
moreover {
assume ∗: $?upper < 2 \hat{} m * card\text{-}slice\ h\ m$
have $1\ /\ (1 + \varepsilon) < 1$
using ε *divide-less-eq-1* **by** *fastforce*
then have $\varepsilon\ /\ (1 + \varepsilon) < \varepsilon$
using ε
by (*metis* (*no-types*, *opaque-lifting*) *add-cancel-left-right div-by-1 divide-divide-eq-left divide-less-eq-1-pos mult.commute nonzero-divide-mult-cancel-left*)
then have $card\ (proj\ S\ W) * (1 + \varepsilon\ /\ (1 + \varepsilon)) \le ?upper$

```
      using linorder-not-less not-less-iff-gr-or-eq by fastforce
    then have (card (proj S W) * (1 + ε / (1 + ε))) / 2 ^ m <
card-slice h m
      apply (intro real-divide-pos-right)
      using * by auto
    then have h ∈ U m unfolding U-def
      by (simp add: μ-def)
  }
  ultimately have h ∈ L m ∨ h ∈ U m by blast
  then have ∀ m∈{Suc 0..<card S}.
        h ∈ T m ⟶
        h ∈ T (m − Suc 0) ∨
        h ∉ L m ∧ h ∉ U m ⟹
      h ∈ T (card S − Suc 0) ⟹ False
    using m 1 by auto
 }
 ultimately show
   h ∈ (⋃ i∈{1..<card S}.
          (T i − T (i − 1)) ∩ (L i ∪ U i)) ∪
        − T (card S − 1)
  by auto
qed


lemma smallest-nat-exists:
 assumes P i ¬P (0::nat)
 obtains m where m ≤ i P m ¬P (m−1)
 using assms
proof (induction i)
 case 0
 then show ?case by auto
next
 case (Suc i)
 then show ?case
  by (metis diff-Suc-1 le-Suc-eq)
qed

lemma mstar-non-zero:
 shows ¬ μ 0 * (1 + ε / (1 + ε)) ≤ thresh
proof −
 have μ 0 ≥ thresh
  unfolding μ-def
  by (auto simp add: thresh(2))
 thus ?thesis
  by (smt (verit, best) ε μ-gt-zero divide-pos-pos mult-le-cancel-left2)
qed

lemma real-div-less:
 assumes c > 0
```

assumes $a \leq b * (c::nat)$
shows $real\ a\ /\ real\ c \leq b$
by (*metis assms*(1) *assms*(2) *divide-le-eq of-nat-0-less-iff of-nat-mono of-nat-mult*)

lemma *mstar-exists*:
obtains m **where**
$\mu\ (m - 1) * (1 + \varepsilon\ /\ (1 + \varepsilon)) > thresh$
$\mu\ m * (1 + \varepsilon\ /\ (1 + \varepsilon)) \leq thresh$
$m \leq card\ S - 1$
proof −
have *e1*:$1 + \varepsilon\ /\ (1 + \varepsilon) > 1$
by (*simp add*: ε *add-nonneg-pos*)
have *e2*:$1 + \varepsilon\ /\ (1 + \varepsilon) < 2$
by (*simp add*: ε *add-nonneg-pos*)
have $thresh\ \geq (4::real)$
using *thresh*(1) **by** *linarith*
then have *up*:$thresh\ /\ (1 + \varepsilon\ /\ (1 + \varepsilon)) > 2$
by (*smt* (*verit*) *e1 e2 field-sum-of-halves frac-less2*)

have $card\ (proj\ S\ W) \leq 2 * 2\ \hat{}\ (card\ S - Suc\ 0)$
by (*metis One-nat-def S Suc-diff-Suc card.empty card-gt-0-iff card-proj*(2) *diff-zero less-one order-less-le-trans plus-1-eq-Suc power-0 power-Suc0-right power-add thresh*(1) *thresh*(2) *zero-neq-numeral*)

then have *low*:$\mu\ (card\ S - 1) \leq 2$
unfolding μ-*def*
using *real-div-less*
by (*smt* (*verit*) *Num.of-nat-simps*(2) *Num.of-nat-simps*(4) *Suc-1 nat-zero-less-power-iff numeral-nat*(7) *of-nat-power plus-1-eq-Suc pos2*)

have *pi*: $\mu\ (card\ S - 1) * (1 + \varepsilon\ /\ (1 + \varepsilon)) \leq thresh$
using *up low*
by (*smt* (*verit*, *ccfv-SIG*) *divide-le-eq e1*)

from *smallest-nat-exists*[*OF pi mstar-non-zero*]
show *?thesis*
by (*metis linorder-not-less that*)
qed

definition *mstar* :: *nat*
where $mstar = (@m.$
$\mu\ (m - 1) * (1 + \varepsilon\ /\ (1 + \varepsilon)) > thresh \wedge$
$\mu\ m * (1 + \varepsilon\ /\ (1 + \varepsilon)) \leq thresh \wedge$
$m \leq card\ S - 1)$

lemma *mstar-prop*:

shows
$\mu\ (mstar - 1) * (1 + \varepsilon\ /\ (1 + \varepsilon)) > thresh$
$\mu\ mstar * (1 + \varepsilon\ /\ (1 + \varepsilon)) \leq thresh$
$mstar \leq card\ S - 1$
unfolding *mstar-def*
by (*smt* (*verit*) *some-eq-ex mstar-exists*)+

lemma *O1-lem*:
assumes $i \leq m$
shows $(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i) \subseteq T\ m$
using *T-mono assms* **by** *blast*

lemma *O1*:
shows $(\bigcup i \in \{1..mstar-3\}.$
$(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i)) \subseteq T\ (mstar-3)$
using *T-mono* **by** *force*

lemma *T-anti-mono-neg*:
assumes $i \leq j$
shows $-\ T\ j \subseteq -\ T\ i$
by (*simp add*: *Diff-mono T-mono assms*)

lemma *O2-lem*:
assumes $mstar < i$
shows $(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i) \subseteq -T\ mstar$
proof −
have $(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i) \subseteq -T\ (i-1)$
by *blast*
thus *?thesis*
by (*smt* (*verit*) *T-mono ApproxMCCore-axioms One-nat-def Suc-diff-Suc Suc-le-eq assms compl-mono diff-is-0-eq' diff-less-mono leI minus-nat.diff-0 subset-trans*)
qed

lemma *O2*:
shows $(\bigcup i \in \{mstar..<card\ S\}.$
$(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i)) \cup$
$-T\ (card\ S - 1) \subseteq L\ mstar \cup U\ mstar$
proof −
have *0*: $(\bigcup i \in \{mstar..<card\ S\}.$
$(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i)) \subseteq$
$(T\ mstar - T\ (mstar-1)) \cap (L\ mstar \cup U\ mstar) \cup$
$(\bigcup i \in \{mstar+1..<card\ S\}.$
$(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i))$
apply (*intro subsetI*)
apply *clarsimp*
by (*metis Suc-le-eq atLeastLessThan-iff basic-trans-rules*(*18*))

have *1*: $(\bigcup i \in \{mstar+1..<card\ S\}.$

$(T\ i\ -\ T\ (i-1)) \cap (L\ i \cup U\ i)) \subseteq -T\ mstar$
apply *clarsimp*
by (*metis* (*no-types*, *lifting*) *ApproxMCCore.T-mono ApproxMC-Core-axioms One-nat-def diff-Suc-1 diff-le-mono subsetD*)

have *2*: $-T\ (card\ S\ -\ 1) \subseteq -\ T\ mstar$
using *T-anti-mono-neg mstar-prop*(*3*) **by** *presburger*

have $thresh \geq \mu\ mstar * (1 + \varepsilon\ /\ (1 + \varepsilon))$
using *mstar-prop*(*2*) *thresh* **by** *linarith*

then have $*$: $-\ T\ mstar \subseteq U\ mstar$
unfolding *T-def U-def*
by *auto*

have $(\bigcup i \in \{mstar..<card\ S\}.$
$(T\ i\ -\ T\ (i-1)) \cap (L\ i \cup U\ i)) \cup$
$-T\ (card\ S\ -\ 1) \subseteq$
$((T\ mstar\ -\ T\ (mstar-1)) \cap (L\ mstar \cup U\ mstar)) \cup -T\ mstar$
using *0 1 2* **by** (*smt* (*z3*) *Un-iff subset-iff*)

moreover have $... \subseteq L\ mstar \cup U\ mstar$
using $*$
by *blast*
ultimately show *?thesis* **by** *auto*
qed

lemma *O3*:
assumes $i \leq mstar\ -\ 1$
shows $(T\ i\ -\ T\ (i-1)) \cap (L\ i \cup U\ i) \subseteq L\ i$
proof −
have $*$: $\mu\ i * (1 + \varepsilon\ /\ (1 + \varepsilon)) > thresh$
by (*smt* (*verit*, *ccfv-SIG*) ε *μ-anti-mono assms divide-nonneg-nonneg mstar-prop*(*1*) *mult-right-mono*)

have $x \in T\ i \wedge x \in U\ i \Longrightarrow False$ **for** x
unfolding *T-def U-def*
using $*$ **by** *auto*
thus *?thesis*
by *blast*
qed

lemma *union-split-lem*:
assumes x: $x \in (\bigcup i \in \{1..<n::nat\}.\ P\ i)$
shows $x \in (\bigcup i \in \{1..m-3\}.\ P\ i) \cup$
$P\ (m-2) \cup$
$P\ (m-1) \cup$
$(\bigcup i \in \{m..<n\}.\ P\ i)$

proof −
obtain i **where** i: $i \in \{1..<n\}$
$x \in P\ i$ **using** x **by** *auto*
have $i \in \{1..m-3\} \vee i = m-2 \vee i = m-1 \vee i \in \{m..<n\}$
using $i(1)$
by *auto*
thus *?thesis* **using** i
by *blast*
qed

lemma *union-split*:
$(\bigcup i{\in}\{1..<n{::}nat\}.\ P\ i) \subseteq$
$(\bigcup i{\in}\{1..m-3\}.\ P\ i) \cup$
$P\ (m-2) \cup$
$P\ (m-1) \cup$
$(\bigcup i{\in}\{m..<n\}.\ P\ i)$
using *union-split-lem*
by (*metis subsetI*)

lemma *failure-bound*:
shows *approxcore-fail* $\subseteq$
$T\ (mstar-3) \cup$
$L\ (mstar-2) \cup$
$L\ (mstar-1) \cup$
$(L\ mstar \cup U\ mstar)$
proof −

have $*$: *approxcore-fail* $\subseteq$
$(\bigcup i{\in}\{1..<card\ S\}.$
$(T\ i - T\ (i-1)) \cap (L\ i \cup U\ i)) \cup -T\ (card\ S - 1)$ (**is** - $\subseteq$
$(\bigcup i{\in}\{1..<card\ S\}.\ ?P\ i) \cup$ -)
using *failure-imp* **.**

moreover have ... $\subseteq$
$(\bigcup i{\in}\{1..mstar - 3\}.\ ?P\ i) \cup$
$?P\ (mstar - 2) \cup$
$?P\ (mstar - 1) \cup$
$((\bigcup i{\in}\{mstar..<card\ S\}.\ ?P\ i) \cup -T\ (card\ S - 1))$
using
union-split[*of* $\lambda i.\ ?P\ i$ *card S mstar*]
by *blast*
moreover have ... $\subseteq$
$T\ (mstar - 3) \cup$
$L\ (mstar - 2) \cup$
$L\ (mstar - 1) \cup$
$(L\ mstar \cup U\ mstar)$

using *O1 O2 O3*
by (*metis* (*no-types*, *lifting*) *One-nat-def Un-mono diff-Suc-eq-diff-pred*

diff-le-self nat-1-add-1 plus-1-eq-Suc)
ultimately show *?thesis*
by (*meson order-trans*)
qed

end

end

5 ApproxMCCore analysis

This section analyzes ApproxMCCore with respect to a universal hash family. The proof follows Lemmas 1 and 2 from Chakraborty et al. [1].

theory *ApproxMCCoreAnalysis* **imports**
ApproxMCCore
begin

definition *Hslice* :: *nat* ⇒
(*'a assg* ⇒ *'b* ⇒ *nat assg*) ⇒ (*'a assg* ⇒ *'b* ⇒ *nat assg*)
where *Hslice i H* = (λ*w s*. *aslice i* (*H w s*))

context *prob-space*
begin

lemma *indep-vars-prefix*:
assumes *indep-vars* (λ-. *count-space UNIV*) *H J*
shows *indep-vars* (λ-. *count-space UNIV*) (*Hslice i H*) *J*
proof −
have *indep-vars* (λ-. *count-space UNIV*) (λ*y*. (λ*x*. *aslice i x*) ∘ *H y*) *J*
by (*auto intro*!: *indep-vars-compose*[*OF assms*(*1*)])
thus *?thesis*
unfolding *o-def Hslice-def*
by *auto*
qed

lemma *assg-nonempty-dom*:
shows
(λ*x*. *if x* < *i then Some True else None*) ∈
{α::*nat assg*. *dom* α = {*0*..<*i*}}
by (*auto split*: *if-splits*)

lemma *card-dom-ran-nat-assg*:
shows *card* {α::*nat assg*. *dom* α = {*0*..<*n*}} = *2*^*n*
proof −
have ∗: {α::*nat assg*. *dom* α = {*0*..<*n*}} =

```
    {w. dom w = {0..<n} ∧ ran w ⊆ {True,False}}
    by auto
  have finite {0..<n} by auto
  from card-dom-ran[OF this]
  have card {w. dom w = {0..<n} ∧ ran w ⊆ {True,False}} =
    card {True,False} ^ card {0..<n} .
  thus ?thesis
    unfolding *
    by (auto simp add: numeral-2-eq-2)
qed

lemma card-nat-assg-le:
  assumes i ≤ n
  shows card {α::nat assg. dom α = {0..<n}} =
    2^(n−i) * card {α::nat assg. dom α = {0..<i}}
  unfolding card-dom-ran-nat-assg
  by (metis assms le-add-diff-inverse mult.commute power-add)

lemma empty-nat-assg-slice-notin:
  assumes i ≤ n
  assumes dom β ≠ {0..<i}
  shows{α::nat assg. dom α = {0..<n} ∧ aslice i α = β} = {}
proof (intro equals0I)
  fix x
  assume x ∈ {α. dom α = {0..<n} ∧ aslice i α = β}
  then have dom β = {0..<i}
    unfolding aslice-def
    using assms(1) by force
  thus False using assms(2) by blast
qed

lemma restrict-map-dom:
  shows α |` dom α = α
  unfolding restrict-map-def fun-eq-iff
  by (simp add: domIff)

lemma aslice-refl:
  assumes dom α = {..<i}
  shows aslice i α = α
  unfolding aslice-def assms[symmetric]
  using restrict-map-dom by auto

lemma bij-betw-with-inverse:
  assumes f ` A ⊆ B
  assumes ⋀x. x ∈ A ⟹ g (f x) = x
  assumes g ` B ⊆ A
  assumes ⋀x. x ∈ B ⟹ f (g x) = x
  shows bij-betw f A B
proof −
```

```
  have inj-on f A
    by (metis assms(2) inj-onI)

  thus ?thesis
    unfolding bij-betw-def
    using assms
    by (metis image-subset-iff subsetI subset-antisym)
qed

lemma card-nat-assg-slice:
  assumes i ≤ n
  assumes dom β = {0..<i}
  shows card {α::nat assg. dom α = {0..<n} ∧ aslice i α = β} =
    2 ^ (n−i)
proof −
  have dom α = {0..<i} ∧ aslice i α = β ⟷ α = β for α
    using aslice-refl
    by (metis assms(2) lessThan-atLeast0)
  then have r2:
    {α::nat assg. dom α = {0..<i} ∧ aslice i α = β} = {β}
    by simp

  define f where f =
    (λ(α::nat assg,β::nat assg) j.
    if j < i then β j else α (j−i))
  let ?lhs = ({α. dom α = {0..<n − i}} ×
     {α. dom α = {0..<i} ∧ aslice i α = β})
  let ?rhs = {α::nat assg. dom α = {0..<n} ∧ aslice i α = β}

  define finv where finv =
    (λfab::nat assg.
      ((λj. fab (j + i)),
       fab |` {..<i})
    )
  have 11: ⋀x. dom (f x) = {j. if j < i then j ∈ dom (snd x) else j
− i ∈ dom (fst x)}
    unfolding f-def
      by (auto simp add: fun-eq-iff split: if-splits)
  have 1: f ` ?lhs ⊆ ?rhs
  proof standard
    fix x
    assume x: x ∈ f ` ({α. dom α = {0..<n − i}} × {α. dom α =
{0..<i} ∧ aslice i α = β})
    obtain a b where ab: dom a = {0..<n − i} dom b = {0..<i}
      x = f (a,b)
      using x by blast
    have 1: dom x = {0..<n}
      unfolding ab 11 using assms(1)
      by (auto simp add: ab)
```

```
  have 2: aslice i x = β
    using x unfolding f-def
    by (auto simp add: aslice-def restrict-map-def split: if-splits)
  show  x ∈ {α. dom α = {0..<n} ∧ aslice i α = β}
    using 1 2 by blast
qed

have  dom a = {0..<n − i} ⟹
      dom b = {0..<i} ⟹
      ∀x. aslice i b x = β x ⟹
      ¬ x < i ⟹ None = b x for a b :: nat assg and x
  by (metis atLeastLessThan-iff domIff)
then have 2: ⋀x. x ∈ ?lhs ⟹ finv (f x) = x
  unfolding finv-def f-def
  by (clarsimp simp add: fun-eq-iff restrict-map-def)

have 31: ⋀fab x y.
      dom fab = {0..<n} ⟹
      β = aslice i fab ⟹
      fab (x + i) = Some y ⟹
      x < n − i
  by (metis atLeastLessThan-iff domI less-diff-conv)
also have ⋀fab x.
      dom fab = {0..<n} ⟹
      β = aslice i fab ⟹
      x < i ⟹ ∃y. fab x = Some y
 by (metis assms(1) domD dual-order.trans lessThan-atLeast0 lessThan-iff
linorder-not-less)
ultimately have 3: finv ‘ ?rhs ⊆ ?lhs
  unfolding finv-def
  by (auto simp add: aslice-def split: if-splits)

have 4: ⋀x. x ∈ ?rhs ⟹ f (finv x) = x
  unfolding finv-def f-def
  by (auto simp add: fun-eq-iff restrict-map-def)

have bij-betw f ?lhs ?rhs
  by (auto intro: bij-betw-with-inverse[OF 1 2 3 4])

from bij-betw-same-card[OF this]
have
card {α::nat assg. dom α = {0..<n} ∧ aslice i α = β} =
 card ({α::nat assg. dom α = {0..<n−i}} ×
      {α::nat assg. dom α = {0..<i} ∧ aslice i α = β})
  by auto
moreover have ... = 2^(n−i)
  using r2 card-dom-ran-nat-assg
  by (simp add: card-cartesian-product)
```

ultimately show *?thesis* **by** *auto*
qed

lemma *finite-dom*:
assumes *finite V*
shows *finite* $\{w :: 'a \rightharpoonup bool.\ dom\ w = V\}$
proof −
have ∗: $\{w :: 'a \rightharpoonup bool.\ dom\ w = V\} =$
$\{w.\ dom\ w = V \wedge ran\ w \subseteq \{True,False\}\}$
by *auto*
show *?thesis* **unfolding** ∗
apply (*intro finite-set-of-finite-maps*)
using *assms* **by** *auto*
qed

lemma *universal-prefix-family-from-hash*:
assumes *M*: $M = measure\text{-}pmf\ p$
assumes *kH*: $k\text{-}universal\ k\ H\ D\ \{\alpha::nat\ assg.\ dom\ \alpha = \{0..<n\}\}$
assumes *i*: $i \leq n$
shows $k\text{-}universal\ k\ (Hslice\ i\ H)\ D\ \{\alpha.\ dom\ \alpha = \{0..<i\}\}$
proof −
have $k\text{-}wise\text{-}indep\text{-}vars\ k\ (\lambda\text{-}.\ count\text{-}space\ UNIV)\ H\ D$
using *kH* **unfolding** *k-universal-def*
by *auto*
then have *1*: $k\text{-}wise\text{-}indep\text{-}vars\ k\ (\lambda\text{-}.\ count\text{-}space\ UNIV)\ (Hslice\ i\ H)\ D$
unfolding *k-wise-indep-vars-def*
using *indep-vars-prefix*
by *auto*

have *fdom*: $finite\ \{\alpha::nat\ assg.\ dom\ \alpha = \{0..<i\}\}$
using *measure-pmf.finite-dom* **by** *blast*
have *nempty*: $\{\alpha::nat\ assg.\ dom\ \alpha = \{0..<i\}\} \neq \{\}$
using *assg-nonempty-dom*
by (*metis empty-iff*)
have *2*: $x \in D \Longrightarrow$
$uniform\text{-}on\ (Hslice\ i\ H\ x)\ \{\alpha.\ dom\ \alpha = \{0..<i\}\}$ **for** *x*
proof −
assume $x \in D$
then have *unif*: $uniform\text{-}on\ (H\ x)\ \{\alpha.\ dom\ \alpha = \{0..<n\}\}$
by (*metis kH k-universal-def*)
show $uniform\text{-}on\ (Hslice\ i\ H\ x)\ \{\alpha.\ dom\ \alpha = \{0..<i\}\}$
proof (*intro uniform-onI*[*OF M fdom nempty*])
fix β
have ∗: $\{\omega \in space\ M.\ H\ x\ \omega \in \{\alpha.\ aslice\ i\ \alpha = \beta\}\} =$
$\{\omega.\ Hslice\ i\ H\ x\ \omega = \beta\}$
unfolding *Hslice-def*
by (*auto simp add*: *M*)

```
    have {α::nat assg. dom α = {0..<n}} ∩ {α.  aslice i α = β} =
      {α::nat assg. dom α = {0..<n} ∧ aslice i α = β}
      by auto

    then have (card ({α::nat assg. dom α = {0..<n}} ∩ {α.  aslice
i α = β}))
      = (if dom β = {0..<i} then 2^(n−i) else 0)
     using card-nat-assg-slice[OF i]
     by (simp add: empty-nat-assg-slice-notin i)

   then have **: real (card ({α::nat assg. dom α = {0..<n}} ∩ {α.
aslice i α = β}))
      = indicat-real {α. dom α = {0..<i}} β  * 2^(n−i)
     by simp

    from uniform-onD[OF unif, of {α. aslice i α = β}]
    have prob {ω. Hslice i H x ω = β} =
      real (card ({α. dom α = {0..<n}} ∩ {α. aslice i α = β})) /
      real (card {α::nat assg. dom α = {0..<n}})
      unfolding * by auto
    moreover have ... =
      indicat-real {α. dom α = {0..<i}} β  * 2^(n−i) /
      real (card {α::nat assg. dom α = {0..<n}})
      unfolding ** by auto
     moreover have ... = indicat-real {α. dom α = {0..<i}} β *
2^(n−i) / 2^n
      by (simp add: card-dom-ran-nat-assg)
    moreover have ... = indicat-real {α. dom α = {0..<i}} β / 2^i
      by (simp add: i power-diff)
     moreover have ... =  indicat-real {α. dom α = {0..<i}} β /
real ((2^i)::nat) by auto
     moreover have ... =  indicat-real {α. dom α = {0..<i}} β /
real (card {α::nat assg. dom α = {0..<i}})
      using card-dom-ran-nat-assg
      by auto
    ultimately show prob {ω. Hslice i H x ω = β} =
       indicat-real {α. dom α = {0..<i}} β /
       real (card {α::nat assg. dom α = {0..<i}})
      by presburger
   qed
  qed
  show ?thesis
   unfolding k-universal-def
   using 1 2
   by blast
qed

end
```

context *ApproxMCCore*
begin

definition *pivot* :: *real*
  where *pivot* = *9.84* ∗ (*1* + *1* / ε)^2

context
  assumes *thresh*: *thresh* ≥ (*1* + ε / (*1* + ε)) ∗ *pivot*
begin

lemma *aux-1*:
  assumes *fin*:*finite* (*set-pmf p*)
  assumes σ: σ > *0*
  assumes *exp*: μ *i* = *measure-pmf.expectation p Y*
  assumes *var*: σ^2 = *measure-pmf.variance p Y*
  assumes *var-bound*: σ^2 ≤ μ *i*
  shows
    measure-pmf.prob p {*y*. | *Y y* − μ *i* | ≥ ε / (*1* + ε) ∗ μ *i* }
    ≤ (*1* + ε)^2 / (ε^2 ∗ μ *i*)
proof −
  have *pvar*: *measure-pmf.variance p Y* > *0*
    using *var* σ
    by (*metis zero-less-power*)
  have *kmu*: ε ∗ (μ *i*) / ((*1* + ε) ∗ σ) > *0*
    using σ *pvar var var-bound*
    using ε **by** *auto*
  have *mupos*: μ *i* > *0*
    using *pvar var var-bound* **by** *linarith*
  from *spec-chebyshev-inequality* [*OF fin pvar kmu*]
  have *measure-pmf.prob p*
    {*y*. (*Y y* − *measure-pmf.expectation p Y*)^2 ≥
      (ε ∗ (μ *i*) / ((*1* + ε) ∗ σ))^2 ∗ *measure-pmf.variance p Y*} ≤
1 / (ε ∗ (μ *i*) / ((*1* + ε) ∗ σ))^2
    by *simp*
  then have *ineq1*:*measure-pmf.prob p*
    {*y*. (*Y y* − μ *i*)^2 ≥
      (ε ∗ (μ *i*) / ((*1* + ε) ∗ σ))^2 ∗ σ^2} ≤ *1* / (ε ∗ (μ *i*) / ((*1* +
ε) ∗ σ))^2
    using *exp var* **by** *simp*
  have (λ*y*. (*Y y* − μ *i*)^2 ≥ (ε ∗ (μ *i*) / ((*1* + ε) ∗ σ))^2 ∗ σ^2)
      = (λ*y*. (*Y y* − μ *i*)^2 ≥ (ε ∗ (μ *i*) / ((*1* + ε) ∗ σ) ∗ σ)^2)
    by (*metis power-mult-distrib*)
  moreover have ... = (λ*y*. | *Y y* − μ *i* | ≥ ε ∗ (μ *i*) / ((*1* + ε) ∗ σ)
∗ σ)
  proof −
    have *0* ≤ ε ∗ μ *i* / (*1* + ε)
      by (*simp add*: ε *less-eq-real-def mupos zero-compare-simps*(*1*))
    then show *?thesis*

```
    apply clarsimp
    by (metis abs-le-square-iff abs-of-nonneg)
  qed
  moreover have ... = (λy. | Y y − μ i | ≥ ε * (μ i) / (1 + ε))
    using σ by auto
  ultimately have simp1:(λy. (Y y − μ i)^2 ≥ (ε * (μ i) / ((1 +
ε) * σ))^2 * σ^2)
                = (λy. | Y y − μ i | ≥ ε / (1 + ε) * (μ i))
    by auto

  have σ^2/(μ i)^2 ≤ (μ i)/(μ i)^2
    using var-bound μ-gt-zero
    by (simp add: divide-right-mono)
  moreover have ... = 1 / (μ i)
    by (simp add: power2-eq-square)
  ultimately have simp2: σ^2/(μ i)^2 ≤ 1 / (μ i) by auto

  have measure-pmf.prob p {y. | Y y − μ i | ≥ ε / (1 + ε) * (μ i)}
       ≤ 1 / (ε * (μ i) / ((1 + ε) * σ))^2
    using ineq1 simp1
    by auto
  moreover have ... = (1 + ε)^2 / ε^2 * σ^2/(μ i)^2
    by (simp add: power-divide power-mult-distrib)
  moreover have ... ≤ (1 + ε)^2 / ε^2 * (1 / (μ i))
    using simp2
   by (smt (verit, best) ε divide-pos-pos mult-left-mono times-divide-eq-right
zero-less-power)
  ultimately have measure-pmf.prob p {y. | Y y − μ i | ≥ ε / (1 +
ε) * (μ i)}
                  ≤ (1 + ε)^2 / (ε^2 * (μ i))
    by auto
  thus ?thesis by auto
qed


lemma analysis-1-1:
  assumes p: finite (set-pmf p)
  assumes ind: prob-space.k-universal (measure-pmf p) 2 H
    {α::'a assg. dom α = S}
    {α::nat assg. dom α = {0..<card S − 1}}
  assumes i: i ≤ card S − 1
  shows
    measure-pmf.prob p
    {s. | card-slice ((λw. H w s)) i − μ i | ≥ ε / (1 + ε) * μ i}
    ≤ (1 + ε)^2 / (ε^2 * μ i)
proof −


  define var where var =
```

```
    (λi. measure-pmf.variance p
      (λs. real (card (proj S W ∩
        {w. Hslice i H w s = aslice i α}))))

from prob-space.universal-prefix-family-from-hash[OF - - ind]
have hf: prob-space.k-universal (measure-pmf p) 2
 (Hslice i H) {α::'a assg. dom α = S} {α. dom α = {0..<i}}
  using prob-space-measure-pmf
  using i ind prob-space.universal-prefix-family-from-hash
  by blast

have pSW: proj S W ⊆ {α. dom α = S}
  unfolding proj-def restr-def by (auto split:if-splits)

have ain: aslice i α ∈ {α. dom α = {0..<i}} using α
  unfolding aslice-def using i by auto

from k-universal-expectation-eq[OF p hf finite-proj-S pSW ain]
have exp:measure-pmf.expectation p
 (λs. real (card (proj S W ∩
                {w. Hslice i H w s = aslice i α}))) =
  real (card (proj S W)) /
  real (card {α::nat assg. dom α = {0..<i}}) .

have exp-mu:real (card (proj S W)) /
  real (card {α::nat assg. dom α = {0..<i}}) = μ i
  unfolding μ-def
  by (simp add: measure-pmf.card-dom-ran-nat-assg)

have proj S W ∩
          {w. Hslice i H w s = aslice i α} =
  proj S W ∩ {w. hslice i (λw. H w s) w =  aslice i α} for s
  unfolding proj-def Hslice-def hslice-def
  by auto
then have extend-card-slice:
  ⋀s. (card (proj S W ∩ {w. Hslice i H w s = aslice i α})) =
  card-slice ((λw. H w s)) i
  unfolding card-slice-def by auto

have mu-exp: μ i = measure-pmf.expectation p
 (λs. real (card (proj S W ∩ {w. Hslice i H w s = aslice i α})))
  using exp exp-mu by auto

from two-universal-variance-bound[OF p hf finite-proj-S pSW ain]
have
  var i ≤
  measure-pmf.expectation p
    (λs. real (card (proj S W ∩
                  {w. Hslice i H w s = aslice i α})))
```

```
    unfolding var-def .
  then have var-bound: var i ≤ μ i using exp exp-mu
    by linarith

  have var i ≥ 0 unfolding var-def by auto
  then have var i > 0 ∨  var i = 0 by auto
  moreover {
    assume var i = 0

    then have 1:
      measure-pmf.expectation p
        (λs. (card-slice (λw. H w s) i − μ i)^2) = 0
      unfolding var-def extend-card-slice mu-exp by auto

    have 2: measure-pmf.expectation p
        (λs. (card-slice (λw. H w s) i − μ i)^2) =
      sum (λs. (card-slice (λw. H w s) i − μ i)^2 ∗ pmf p s) (set-pmf
p)
      using assms by (auto intro!: integral-measure-pmf-real)

    have ∀x ∈ set-pmf p. (card-slice (λw. H w x) i − μ i)^2 ∗ pmf p
x = 0
      apply (subst sum-nonneg-eq-0-iff[symmetric])
      using 1 2 p by auto
    then have ∗: ⋀x. x ∈ set-pmf p ⟹ (card-slice (λw. H w x) i −
μ i)^2 = 0
      by (meson mult-eq-0-iff set-pmf-iff)

    have ∗∗: (1 + ε)^2 / (ε^2 ∗ μ i) > 0
      using μ-gt-zero ε by auto
    have ε / (1 + ε) ∗ μ i > 0
      using μ-gt-zero ε by auto
    then have ⋀s. s ∈ set-pmf p ⟹ | card-slice ((λw. H w s)) i − μ
i | < ε / (1 + ε) ∗ μ i
      using ∗ by auto
    then have
    measure-pmf.prob p
    {s. | card-slice ((λw. H w s)) i − μ i | ≥ ε / (1 + ε) ∗ μ i } = 0
      apply (subst measure-pmf-zero-iff)
      using linorder-not-less by auto
    then have
    measure-pmf.prob p
      {s. | card-slice ((λw. H w s)) i − μ i | ≥ ε / (1 + ε) ∗ μ i }
      ≤ (1 + ε)^2 / (ε^2 ∗ μ i)
      using ∗∗ by auto
  }
  moreover {
    define sigma where sigma = sqrt(var i)
    assume var i > 0
```

```
  then have sigma-gt-0: sigma > 0
    unfolding sigma-def by simp

  have extend-sigma: sigma^2 = measure-pmf.variance p
      (λs. real (card (proj S W ∩
      {w. Hslice i H w s = aslice i α})))
    unfolding sigma-def var-def
   using less-eq-real-def local.var-def real-sqrt-pow2 sigma-def sigma-gt-0
    by fastforce

  have sigma-bound: sigma^2 ≤ μ i
    using var-bound sigma-gt-0
    using sigma-def by force

  from aux-1[OF p sigma-gt-0 mu-exp extend-sigma sigma-bound]
  have
    measure-pmf.prob p
    {s. | card-slice ((λw. H w s)) i − μ i | ≥ ε / (1 + ε) ∗ μ i }
    ≤ (1 + ε)^2 / (ε^2 ∗ μ i)
    using extend-card-slice by auto
 }

 ultimately show ?thesis by auto
qed


lemma analysis-1-2:
 assumes p: finite (set-pmf p)
 assumes ind: prob-space.k-universal (measure-pmf p) 2 H
   {α::'a assg. dom α = S}
   {α::nat assg. dom α = {0..<card S − 1}}
 assumes i: i ≤ card S − 1
 assumes β: β ≤ 1
 shows measure-pmf.prob p
   {s. real(card-slice ((λw. H w s)) i) ≤ β ∗ μ i }
   ≤ 1 / (1 + (1 − β)^2 ∗ μ i)
proof −
 have ∗: (⋀s. (0::real) ≤ card-slice ((λw. H w s)) i)
   by simp
 from spec-paley-zygmund-inequality[OF p ∗ β]
 have paley-zigmund:
   (measure-pmf.variance p (λs. real(card-slice ((λw. H w s)) i) )
   + (1−β)^2 ∗ (measure-pmf.expectation p (λs. card-slice ((λw. H
w s)) i))^2) ∗
    measure-pmf.prob p {s. real(card-slice ((λw. H w s)) i) > β ∗
measure-pmf.expectation p (λs. real(card-slice ((λw. H w s)) i) )} ≥
   (1−β)^2 ∗ (measure-pmf.expectation p (λs. real(card-slice ((λw.
H w s)) i) ))^2
```

```
  by auto
define var where var = (λi. measure-pmf.variance p
    (λs. real (card (proj S W ∩
    {w. Hslice i H w s = aslice i α}))))

from prob-space.universal-prefix-family-from-hash[OF - - ind]
have hf: prob-space.k-universal (measure-pmf p) 2
 (Hslice i H) {α::'a assg. dom α = S} {α. dom α = {0..<i}}
  using prob-space-measure-pmf
  using i ind prob-space.universal-prefix-family-from-hash
  by blast

have pSW: proj S W ⊆ {α. dom α = S}
  unfolding proj-def restr-def
  by (auto split:if-splits)

have ain: aslice i α ∈ {α. dom α = {0..<i}} using α
  unfolding aslice-def using i by auto

from k-universal-expectation-eq[OF p hf finite-proj-S pSW ain]
have exp:measure-pmf.expectation p
 (λs. real (card (proj S W ∩
                {w. Hslice i H w s = aslice i α}))) =
  real (card (proj S W)) /
  real (card {α::nat assg. dom α = {0..<i}}) .

have exp-mu:real (card (proj S W)) /
  real (card {α::nat assg. dom α = {0..<i}}) = μ i
  unfolding μ-def
  by (simp add: measure-pmf.card-dom-ran-nat-assg)

have proj S W ∩
          {w. Hslice i H w s = aslice i α} =
  proj S W ∩ {w. hslice i (λw. H w s) w =  aslice i α} for s
  unfolding proj-def Hslice-def hslice-def
  by auto

then have extend-card-slice:⋀s. (card (proj S W ∩
                {w. Hslice i H w s = aslice i α})) =
  card-slice ((λw. H w s)) i
  unfolding card-slice-def by auto

have mu-exp: μ i = measure-pmf.expectation p
 (λs. real (card (proj S W ∩
                {w. Hslice i H w s = aslice i α})))
  using exp exp-mu by auto

from two-universal-variance-bound[OF p hf finite-proj-S pSW ain]
have
```

```
    var i ≤
    measure-pmf.expectation p
      (λs. real (card (proj S W ∩
                    {w. Hslice i H w s = aslice i α})))
    unfolding var-def .
  then have var-bound: var i ≤ μ i using exp exp-mu
    by linarith

  have pos-mu: μ i > 0
    unfolding μ-def
    by (simp add: card-proj-witnesses)

  have comp: measure-pmf.prob p
      {s. β * μ i < real (card-slice (λw. H w s) i)} =
    (1 − measure-pmf.prob p {s. real(card-slice ((λw. H w s)) i) ≤ β
* μ i})
    apply (subst measure-pmf.prob-compl[symmetric])
    by (auto intro!: arg-cong[where f = measure-pmf.prob p])

  have extend-var-bound: measure-pmf.variance p (λs. card-slice ((λw.
H w s)) i) ≤ μ i
    using var-bound
    unfolding var-def
    by (simp add: extend-card-slice)
  then have
    (measure-pmf.variance p (λs. real(card-slice ((λw. H w s)) i))
        + (1−β)^2 * (measure-pmf.expectation p (λs. real(card-slice
((λw. H w s)) i) ) )^2)
      * measure-pmf.prob p {s. real(card-slice ((λw. H w s)) i) > β *
measure-pmf.expectation p (λs. real(card-slice ((λw. H w s)) i) )} ≤
    (μ i + (1−β)^2 * (measure-pmf.expectation p ( λs. real(card-slice
((λw. H w s)) i) ) )^2)
    * measure-pmf.prob p
        {s. real(card-slice ((λw. H w s)) i) > β * measure-pmf.expectation
p (λs. real(card-slice ((λw. H w s)) i) )}
    by (auto intro!: mult-right-mono)
  moreover have
   ... ≤ (μ i + (1−β)^2 * (measure-pmf.expectation p ( λs. real(card-slice
((λw. H w s)) i) ) )^2)
    * measure-pmf.prob p
        {s. real(card-slice ((λw. H w s)) i) > β * measure-pmf.expectation
p (λs. real(card-slice ((λw. H w s)) i) )}
    by fastforce
  ultimately have
    (μ i + (1−β)^2 * (μ i)^2) * measure-pmf.prob p {s. real(card-slice
((λw. H w s)) i) > β * μ i} ≥ (1−β)^2 * (μ i)^2
    unfolding mu-exp extend-card-slice
    using paley-zigmund by linarith
  then have
```

$(1 + (1-\beta)\hat{}2 * (\mu\ i)) * (\mu\ i) * measure\text{-}pmf.prob\ p\ \{s.\ real(card\text{-}slice\ ((\lambda w.\ H\ w\ s))\ i) > \beta * \mu\ i\} \geq (1-\beta)\hat{}2 * (\mu\ i) * (\mu\ i)$
by (*smt* (*verit*) *left-diff-distrib' more-arith-simps*(*11*) *mult-cancel-right mult-cancel-right2 power2-eq-square*)
then have
$(1 + (1-\beta)\hat{}2 * (\mu\ i)) * measure\text{-}pmf.prob\ p\ \{s.\ real(card\text{-}slice\ ((\lambda w.\ H\ w\ s))\ i) > \beta * \mu\ i\} \geq (1-\beta)\hat{}2 * (\mu\ i)$
using *pos-mu* **by** *force*
then have
$(1 + (1-\beta)\hat{}2 * (\mu\ i)) * (1 - measure\text{-}pmf.prob\ p\ \{s.\ real(card\text{-}slice\ ((\lambda w.\ H\ w\ s))\ i) \leq \beta * \mu\ i\}) \geq (1-\beta)\hat{}2 * (\mu\ i)$
using *comp* **by** *auto*
then have
$(1 + (1-\beta)\hat{}2 * (\mu\ i)) - (1 + (1-\beta)\hat{}2 * (\mu\ i)) * measure\text{-}pmf.prob\ p\ \{s.\ real(card\text{-}slice\ ((\lambda w.\ H\ w\ s))\ i) \leq \beta * \mu\ i\} \geq (1-\beta)\hat{}2 * (\mu\ i)$
by (*simp add*: *right-diff-distrib*)
then have
$(1 + (1-\beta)\hat{}2 * (\mu\ i)) * measure\text{-}pmf.prob\ p\ \{s.\ real(card\text{-}slice\ ((\lambda w.\ H\ w\ s))\ i) \leq \beta * \mu\ i\} \leq 1$
by *simp*
thus *?thesis* **by** (*smt* (*verit*, *best*) *mult-nonneg-nonneg nonzero-mult-div-cancel-left pos-mu real-divide-pos-left zero-le-power2*)
qed

lemma *shift-*μ:
assumes $k \leq i$
shows$\mu\ i * 2\hat{}k = \mu\ (i-k)$
unfolding μ*-def*
by (*auto simp add*: *assms power-diff*)

lemma *analysis-2-1*:
assumes *p*: *finite* (*set-pmf p*)
assumes *ind*: *prob-space.k-universal* (*measure-pmf p*) *2 H*
$\{\alpha::'a\ assg.\ dom\ \alpha = S\}$
$\{\alpha::nat\ assg.\ dom\ \alpha = \{0..<card\ S - 1\}\}$
assumes ε*-up*: $\varepsilon \leq 1$
shows
measure-pmf.prob (*map-pmf* ($\lambda s\ w.\ H\ w\ s$) *p*) (*T* (*mstar*−*3*))
$\leq 1\ /\ 62.5$
proof −
have $1 + 1\ /\ \varepsilon > 0$
by (*simp add*: ε *pos-add-strict*)
then have *pos-pivot*: *pivot* > *0*
unfolding *pivot-def*
by *simp*

have $mstar \geq 4 \vee mstar < 4$ **by** *auto*
moreover {

```
    assume mstar < 4
     then have  measure-pmf.prob (map-pmf (λs w. H w s) p) (T
(mstar−3))
      ≤ 1 / 62.5
      by (auto simp add: T0-empty)
  }
  moreover {
    assume lo-mstar: mstar ≥ 4

    have extend-mu3: μ (mstar−1) * 2^2 = μ (mstar−3)
      apply (subst shift-μ)
      subgoal using lo-mstar by linarith
      using numeral-3-eq-3
      using Suc-1 diff-Suc-eq-diff-pred numeral-nat(7) by presburger

    have ******: 1 + ε / (1 + ε) ≤ 3 / 2
      using ε assms(3) by auto
    have mu-mstar-3-gt-zero: μ (mstar − 3) / 4 > 0
      using μ-gt-zero by simp

    from mstar-prop(1)
    have thresh < μ (mstar − 1) *2^2 / 4 * (1 + ε / (1 + ε))
      by auto
    also have ... = μ (mstar − 3) / 4 * (1 + ε / (1 + ε))
      unfolding extend-mu3 by auto
    also have ... ≤ μ (mstar − 3) / 4 * (3 / 2)
      apply (intro mult-left-mono)
      using ****** mu-mstar-3-gt-zero by auto
    also have ... = 3 / 8 * μ (mstar − 3)
      by auto
    finally have thresh2mu: thresh < 3 / 8 * μ (mstar − 3) .

    have 1 + ε / (1 + ε) > 0
      by (simp add: add-nonneg-pos ε)
    then have μ (mstar−1) > pivot
      using mstar-prop(1) thresh
      by (smt (verit) nonzero-mult-div-cancel-right real-divide-pos-left)
    then have lo-mu-mstar-3: μ (mstar−3) > 4*pivot
      using extend-mu3
      by simp

    have mstar-3: mstar−3 ≤ card S − 1
      using lo-mstar
      using diff-le-self dual-order.trans mstar-prop(3) by blast

    have *: (5 / 8)^2 = ((25 / 64)::real)
      by (auto simp add: field-simps)
    have **:  1 + 25/64 * 4*pivot ≤ 1+ 25 / 64 * μ (mstar − 3)
      using lo-mu-mstar-3
```

by *auto*

have $1 + 1/\varepsilon \geq 2$
by (*simp add*: ε *assms*(3))
then have $(1 + 1/\varepsilon)\hat{}2 \geq 2\hat{}2$
by (*smt* (*verit*) *power-mono*)
then have ***: $1 + 25/64 * 4 * 4*9.84 \leq 1+ 25 / 64 * 4*pivot$
unfolding *pivot-def*
by *auto*
have ****: $1 + 25/64 * 4 * 4*9.84 > (0::real)$
by *simp*

have *measure-pmf.prob p*
$\{s.\ real\ (card\text{-}slice\ (\lambda w.\ H\ w\ s)\ (mstar - 3)) \leq$
$3 / 8 * \mu\ (mstar - 3)\}$
$\leq 1 / (1 + (1 - 3 / 8)^2 * \mu\ (mstar - 3))$
apply(*intro analysis-1-2*[*OF p ind mstar-3*])
by *auto*
also have ... $= 1 / (1 + (5 / 8)\hat{}2 * \mu\ (mstar-3))$
by *simp*
also have ... $= 1 / (1 + 25 / 64 * \mu\ (mstar-3))$
unfolding $*$ **by** *auto*
also have ... $\leq 1 / (1+ 25/64 * 4*pivot)$
using $**$
by (*metis Groups.add-ac*(2) *add-sign-intros*(3) *divide-nonneg-nonneg frac-le mult-right-mono mult-zero-left of-nat-0-le-iff of-nat-numeral order-le-less pos-pivot zero-less-one*)
also have ... $\leq 1 / (1+ 25/64 * 4 * 4*9.84)$
using *** ****
by (*smt* (*verit*) *frac-le*)
also have ... $\leq 1 / 62.5$
by *simp*
finally have *****: *measure-pmf.prob p*
$\{s.\ real\ (card\text{-}slice\ (\lambda w.\ H\ w\ s)\ (mstar - 3)) \leq 3 / 8 * \mu\ (mstar - 3)\} \leq 1 / 62.5$
by *auto*

have *measure-pmf.prob* (*map-pmf* ($\lambda s\ w.\ H\ w\ s$) *p*) (T ($mstar-3$))
$=$ *measure-pmf.prob p* $\{s.\ real\ (card\text{-}slice\ (\lambda w.\ H\ w\ s)\ (mstar - 3)) < thresh\}$
unfolding *T-def*
by *auto*
also have ... $\leq$ *measure-pmf.prob p*
$\{s.\ real\ (card\text{-}slice\ (\lambda w.\ H\ w\ s)\ (mstar - 3)) \leq 3 / 8 * \mu\ (mstar - 3)\}$
using *thresh2mu* **by** (*auto intro*!: *measure-pmf.finite-measure-mono*)
also have ... $\leq 1 / 62.5$
using *****
by *auto*

```
    finally have measure-pmf.prob (map-pmf (λs w. H w s) p) (T
(mstar−3)) ≤ 1 / 62.5 .
  }

  ultimately show ?thesis by auto
qed


lemma analysis-2-1′:
  assumes p: finite (set-pmf p)
  assumes ind: prob-space.k-universal (measure-pmf p) 2 H
    {α::′a assg. dom α = S}
    {α::nat assg. dom α = {0..<card S − 1}}
  shows
    measure-pmf.prob (map-pmf (λs w. H w s) p) (T (mstar−3))
      ≤ 1 / 10.84
proof −
  have 1 + 1 / ε > 0
    by (simp add: ε pos-add-strict)
  then have pos-pivot: pivot > 0
    unfolding pivot-def
    by simp

  have mstar ≥ 4 ∨ mstar < 4 by auto
  moreover {
    assume mstar < 4
     then have  measure-pmf.prob (map-pmf (λs w. H w s) p) (T
(mstar−3))
      ≤ 1 / 10.84
      by (auto simp add: T0-empty)
  }
  moreover {
    assume lo-mstar: mstar ≥ 4

    have extend-mu3: μ (mstar−1) ∗ 2^2 = μ (mstar−3)
      apply (subst shift-μ)
      subgoal using lo-mstar semiring-norm(87) by linarith
      using diff-Suc-eq-diff-pred eval-nat-numeral(3) by presburger

    have ε / (1 + ε) < 1
      using ε by auto
    then have ******: 1 + ε / (1 + ε) < 2
      using ε by auto
    have mu-mstar-3-gt-zero: μ (mstar − 3) / 4 > 0
      using μ-gt-zero by simp

    from mstar-prop(1)
    have thresh < μ (mstar − 1) ∗ (1 + ε / (1 + ε))
      by auto
```

also have ... = μ (*mstar* − *1*) ∗*2^2* / *4* ∗ (*1* + ε / (*1* + ε))
by *auto*
also have ... = μ (*mstar* − *3*) / *4* ∗ (*1* + ε / (*1* + ε))
unfolding *extend-mu3* **by** *auto*
also have ... < μ (*mstar* − *3*) / *4* ∗ *2*
apply (*intro mult-strict-left-mono*)
using ∗∗∗∗∗∗ *mu-mstar-3-gt-zero* **by** *auto*
also have ... = *1* / *2* ∗ μ (*mstar* − *3*)
by *auto*
finally have *thresh2mu*: *thresh* < *1* / *2* ∗ μ (*mstar* − *3*) **.**

have *1* + ε / (*1* + ε) > *0*
by (*simp add*: *add-nonneg-pos* ε)
then have μ (*mstar*−*1*) ∗ *4* > *4*∗*pivot*
using *mstar-prop*(*1*) *thresh*
by (*smt* (*verit*) *nonzero-mult-div-cancel-right real-divide-pos-left*)
then have *lo-mu-mstar-3*: μ (*mstar*−*3*) > *4*∗*pivot*
using *extend-mu3*
by *simp*

have *mstar-3*: *mstar*−*3* ≤ *card S* − *1*
using *lo-mstar*
using *diff-le-self dual-order.trans mstar-prop*(*3*) **by** *blast*

have ∗: (*1* / *2*)^*2* = ((*1* / *4*)::*real*)
by (*auto simp add*: *field-simps*)
have ∗∗: *1* + *1*/*4* ∗ *4*∗*pivot* ≤ *1*+ *1*/*4* ∗ μ (*mstar* − *3*)
using *lo-mu-mstar-3*
by *auto*

have (*1* + *1*/ε)^*2* > *1^2*
by (*simp add*: ε)
then have ∗∗∗: *1* + *1*/*4* ∗ *4*∗*9.84* ≤ *1*+ *1*/*4* ∗ *4* ∗*pivot*
unfolding *pivot-def* **by** *auto*
have ∗∗∗∗: *1* + *1*/*4* ∗ *4* ∗ *9.84* > (*0*::*real*)
by *simp*

have *measure-pmf.prob p*
{*s*. *real* (*card-slice* (λ*w*. *H w s*) (*mstar* − *3*)) ≤
1 / *2* ∗ μ (*mstar* − *3*)}
≤ *1* / (*1* + (*1* − *1* / *2*)^2 ∗ μ (*mstar* − *3*))
apply(*intro analysis-1-2*[*OF p ind mstar-3*])
by *auto*
also have ... = *1* / (*1* + *1* / *4* ∗ μ (*mstar*−*3*))
using ∗ **by** *force*
also have ... ≤ *1* / (*1*+ *1*/*4* ∗ *4*∗*pivot*)
using ∗∗
by (*simp add*: *add-nonneg-pos frac-le pos-pivot*)
also have ... ≤ *1* / (*1*+ *1*/*4* ∗ *4* ∗*9.84*)

```
    using *** ****
    by (smt (verit) frac-le)
  also have ... ≤ 1 / 10.84
    by simp
  finally have *****: measure-pmf.prob p
   {s. real (card-slice (λw. H w s) (mstar − 3)) ≤ 1/2 * μ (mstar
− 3)} ≤ 1 / 10.84 .

  have measure-pmf.prob (map-pmf (λs w. H w s) p) (T (mstar−3))
      = measure-pmf.prob p {s. real (card-slice (λw. H w s) (mstar
− 3)) < thresh}
    unfolding T-def
    by auto
  also have ... ≤ measure-pmf.prob p
   {s. real (card-slice (λw. H w s) (mstar − 3)) ≤ 1 / 2 * μ (mstar
− 3)}
   using thresh2mu by (auto intro!: measure-pmf.finite-measure-mono)
  also have ... ≤ 1 / 10.84
    using *****
    by auto
   finally have measure-pmf.prob (map-pmf (λs w. H w s) p) (T
(mstar−3)) ≤ 1 / 10.84 .
 }

 ultimately show ?thesis by auto
qed


lemma analysis-2-2:
 assumes p: finite (set-pmf p)
 assumes ind: prob-space.k-universal (measure-pmf p) 2 H
   {α::'a assg. dom α = S}
   {α::nat assg. dom α = {0..<card S − 1}}
 shows
   measure-pmf.prob (map-pmf (λs w. H w s) p) (L (mstar−2)) ≤ 1
/ 20.68
proof −
 have epos: 1 + 1 / ε > 0
   by (simp add: ε pos-add-strict)
 then have pos-pivot: pivot > 0
   unfolding pivot-def
   by simp

 have mstar ≥ 3 ∨ mstar < 3 by auto
 moreover {
   assume mstar < 3
    then have  measure-pmf.prob (map-pmf (λs w. H w s) p) (L
(mstar−2))
        ≤ 1 / 20.68
```

by (*auto simp add*: *L0-empty*)
}
moreover {
assume *lo-mstar*: *mstar* ≥ *3*

have *extend-mu2*: *μ* (*mstar*−*1*) ∗ *2*^*1* = *μ* (*mstar*−*2*)
apply (*subst shift-μ*)
subgoal using *lo-mstar* **by** *linarith*
by (*metis diff-diff-left one-add-one*)

have *1* + *ε* / (*1* + *ε*) > *0*
by (*simp add*: *add-nonneg-pos ε*)
then have *μ* (*mstar*−*1*) > *pivot*
using *mstar-prop*(*1*) *thresh*
by (*smt* (*verit*) *nonzero-mult-div-cancel-right real-divide-pos-left*)
then have *lo-mu-mstar-2*: *μ* (*mstar*−*2*) > *2*∗*pivot*
using *extend-mu2*
by *simp*

have *mstar-2*: *mstar*−*2* ≤ *card S* − *1*
using *lo-mstar*
using *diff-le-self dual-order.trans mstar-prop*(*3*) **by** *blast*

have *beta*:*1*/(*1*+*ε*) ≤ (*1*::*real*)
using *ε* **by** *auto*
have *pos*: (*1* / (*1* + *1*/*ε*))^2 > *0*
using *epos* **by** *auto*
then have ∗: *1* + (*1* / (*1* + *1*/*ε*))^2 ∗ *2*∗*pivot* ≤ *1* + (*1* / (*1* + *1*/*ε*))^2 ∗ *μ* (*mstar* − *2*)
using *lo-mu-mstar-2*
by *auto*

have *1* − *1*/(*1*+*ε*) = *1* / (*1* + *1*/*ε*)
by (*smt* (*verit*, *ccfv-threshold*) *ε conjugate-exponent-def conjugate-exponent-real*(*1*))
then have ∗∗: (*1* − *1*/(*1*+*ε*))^*2* = (*1* / (*1* + *1*/*ε*))^*2*
by *simp*
have ∗∗∗: *1* + (*1* / (*1* + *1*/*ε*))^2 ∗ *2* ∗ *9.84* ∗ (*1* + *1*/*ε*)^*2*
= *1* + (*1* / (*1* + *1*/*ε*))^2 ∗ (*1* + *1*/*ε*)^*2* ∗ *2* ∗ *9.84*
by (*simp add*: *mult.commute*)
have ∗∗∗∗: (*1* / (*1* + *1*/*ε*))^2 ∗ (*1* + *1*/*ε*)^*2* = *1*
using *pos*
by (*simp add*: *power-one-over*)

from *analysis-1-2*[*OF p ind mstar-2 beta*]
have *measure-pmf.prob p*
{*s*. *real* (*card-slice* (*λw*. *H w s*) (*mstar* − *2*)) ≤ *1*/(*1*+*ε*) ∗ *μ* (*mstar* − *2*)}
≤ *1* / (*1* + (*1* − *1*/(*1*+*ε*))^2 ∗ *μ* (*mstar* − *2*))

```
    by auto
  also have ... = 1 / (1 + (1 / (1 + 1/ε))^2 * μ (mstar − 2))
    unfolding ** by auto
  also have ... ≤ 1 / (1 + (1 / (1 + 1/ε))^2 * 2 * pivot)
    using *
     by (smt (verit) epos divide-pos-pos frac-le pivot-def pos-prod-le
zero-less-power)
   also have ... = 1 / (1 + (1 / (1 + 1/ε))^2 * 2 * 9.84 * ( 1 +
1/ε )^2)
    unfolding pivot-def by auto
  also have ... = 1 / 20.68
    unfolding *** **** by auto
  finally have *****: measure-pmf.prob p
    {s. real (card-slice (λw. H w s) (mstar − 2)) ≤ 1/(1+ε) * μ
(mstar − 2)} ≤ 1 / 20.68 .

  have measure-pmf.prob p
    {s. real (card-slice (λw. H w s) (mstar − 2)) < 1/(1+ε) * μ
(mstar − 2)}
      ≤ measure-pmf.prob p {s. real (card-slice (λw. H w s) (mstar
− 2)) ≤ 1/(1+ε) * μ (mstar − 2)}
    by (auto intro!: measure-pmf.finite-measure-mono)
  then have ******: measure-pmf.prob p
    {s. real (card-slice (λw. H w s) (mstar − 2)) < 1/(1+ε) * μ
(mstar − 2)}
       ≤ 1 / 20.68
    using ***** by auto

  have measure-pmf.prob (map-pmf (λs w. H w s) p) (L (mstar−2))
      = measure-pmf.prob p
    {s. real (card-slice (λw. H w s) (mstar − 2)) < 1/(1+ε) * μ
(mstar − 2)}
    unfolding L-def
    by auto
  also have ... ≤ 1 / 20.68
    using ****** by auto
   finally have measure-pmf.prob (map-pmf (λs w. H w s) p) (L
(mstar−2)) ≤ 1 / 20.68 .
 }

 ultimately show ?thesis by auto
qed


lemma analysis-2-3:
 assumes p: finite (set-pmf p)
 assumes ind: prob-space.k-universal (measure-pmf p) 2 H
  {α::'a assg. dom α = S}
  {α::nat assg. dom α = {0..<card S − 1}}
```

```
  shows
    measure-pmf.prob
    (map-pmf (λs w. H w s) p) (L (mstar−1)) ≤ 1 / 10.84
proof −
  have epos: 1 + 1 / ε > 0
    by (simp add: ε pos-add-strict)
  then have pos-pivot: pivot > 0
    unfolding pivot-def
    by simp

  have mstar ≥ 2 ∨ mstar < 2 by auto
  moreover {
    assume mstar < 2
     then have  measure-pmf.prob (map-pmf (λs w. H w s) p) (L
(mstar−2))
         ≤ 1 / 10.84
     by (auto simp add: L0-empty)
  }
  moreover {
    assume lo-mstar: mstar ≥ 2

    have 1 + ε / (1 + ε) > 0
      by (simp add: add-nonneg-pos ε)
    then have lo-mu-mstar-1: μ (mstar−1) > pivot
      using mstar-prop(1) using thresh
      by (smt (verit) nonzero-mult-div-cancel-right real-divide-pos-left)

    have mstar-1: mstar−1 ≤ card S − 1
     using lo-mstar diff-le-self dual-order.trans mstar-prop(3) by blast

    have beta: 1/(1+ε) ≤ (1::real)
      using ε by auto
    have (1 / (1 + 1/ε))^2 > 0
      using epos by auto
     then have ∗: 1 + (1 / (1 + 1/ε))^2 ∗ pivot ≤ 1 + (1 / (1 +
1/ε))^2 ∗ μ (mstar − 1)
      using lo-mu-mstar-1
      by auto

    have 1 − 1/(1+ε) = 1 / (1 + 1/ε)
       by (smt (verit, ccfv-threshold) ε conjugate-exponent-def conju-
gate-exponent-real(1))
    then have ∗∗: (1 − 1/(1+ε))^2 = (1 / (1 + 1/ε))^2
      by simp
    have ∗∗∗: 1 + (1 / (1 + 1/ε))^2 ∗ 9.84 ∗ ( 1 + 1/ε )^2
          = 1 + (1 / (1 + 1/ε))^2 ∗ ( 1 + 1/ε )^2 ∗ 9.84
      by (simp add: mult.commute)
    have ∗∗∗∗: (1 / (1 + 1/ε))^2 ∗ ( 1 + 1/ε )^2 = 1
     by (metis (mono-tags, opaque-lifting) ‹0 < 1 + 1 / ε› div-by-1 di-
```

vide-divide-eq-right divide-self-if less-irrefl mult.commute power-mult-distrib power-one)

from *analysis-1-2*[*OF p ind mstar-1 beta*]
have *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) ≤ *1*/(*1*+ε) ∗ μ (*mstar* − *1*)}
≤ *1* / (*1* + (*1* − *1*/(*1*+ε))^2 ∗ μ (*mstar* − *1*))
by *auto*
moreover have ... = *1* / (*1* + (*1* / (*1* + *1*/ε))^2 ∗ μ (*mstar* − *1*))
unfolding ∗∗ **by** *auto*
moreover have ... ≤ *1* / (*1* + (*1* / (*1* + *1*/ε))^2 ∗ *pivot*)
using ∗
by (*smt* (*verit*) ‹*0* < (*1* / (*1* + *1* / ε))^2› *frac-le pos-pivot zero-le-mult-iff*)
moreover have ... = *1* / (*1* + (*1* / (*1* + *1*/ε))^2 ∗ *9.84* ∗ (*1* + *1*/ε)^*2*)
unfolding *pivot-def* **by** *auto*
moreover have ... = *1* / (*1* + (*1* / (*1* + *1*/ε))^2 ∗ (*1* + *1*/ε)^*2* ∗ *9.84*)
unfolding ∗∗∗ **by** *auto*
moreover have ... = *1* / (*1* + *9.84*)
unfolding ∗∗∗∗ **by** *auto*
moreover have ... = *1* / *10.84*
by *auto*
ultimately have ∗∗∗∗∗: *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) ≤ *1*/(*1*+ε) ∗ μ (*mstar* − *1*)} ≤ *1* / *10.84*
by *linarith*
have *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) < *1*/(*1*+ε) ∗ μ (*mstar* − *1*)}
≤ *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) ≤ *1*/(*1*+ε) ∗ μ (*mstar* − *1*)}
by (*auto intro*!: *measure-pmf.finite-measure-mono*)
then have ∗∗∗∗∗∗: *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) < *1*/(*1*+ε) ∗ μ (*mstar* − *1*)}
≤ *1* / *10.84*
using ∗∗∗∗∗ **by** *auto*

have *measure-pmf.prob* (*map-pmf* (λ*s w. H w s*) *p*) (*L* (*mstar*−*1*))
= *measure-pmf.prob p*
{*s. real* (*card-slice* (λ*w. H w s*) (*mstar* − *1*)) < *1*/(*1*+ε) ∗ μ (*mstar* − *1*)}
unfolding *L-def*
by *auto*

```
    moreover have ... ≤ 1 / 10.84
      using ****** by auto
     ultimately have measure-pmf.prob (map-pmf (λs w. H w s) p)
(L (mstar−1)) ≤ 1 / 10.84
      by auto
  }

  ultimately show ?thesis by auto
qed


lemma analysis-2-4:
  assumes p: finite (set-pmf p)
  assumes ind: prob-space.k-universal (measure-pmf p) 2 H
    {α::'a assg. dom α = S}
    {α::nat assg. dom α = {0..<card S − 1}}
  shows
   measure-pmf.prob (map-pmf (λs w. H w s) p) (L mstar ∪ U mstar)
≤ 1 / 4.92
proof −
  have 1 + 1 / ε > 0
    by (simp add: ε pos-add-strict)
  then have pos-pivot: pivot > 0
    unfolding pivot-def
    by simp

  have mstar ≥ 1 ∨ mstar < 1 by auto
  moreover {
    assume mstar < 1
    have LU0-empty: L mstar ∪ U mstar = {}
      using L0-empty U0-empty
      using ‹mstar < 1› less-one by auto
   then have measure-pmf.prob (map-pmf (λs w. H w s) p) (L mstar
∪ U mstar)
         ≤ 1 / 4.92
      by auto
  }
  moreover {
    assume lo-mstar: mstar ≥ 1
    have extend-mu: μ mstar * 2^1 = μ (mstar−1)
      using lo-mstar
      apply (subst shift-μ)
      by auto

    have 1 + ε / (1 + ε) > 0
      by (simp add: add-nonneg-pos ε)
    then have μ (mstar−1) > pivot
      using mstar-prop(1) thresh
      by (smt (verit) nonzero-mult-div-cancel-right real-divide-pos-left)
```

then have *lo-mu-star*: μ *mstar* > *pivot* / *2*
using *extend-mu*
by *auto*

have *mstar*: *mstar* ≤ *card S* − *1*
using *lo-mstar*
using *diff-le-self dual-order.trans mstar-prop*(*3*) **by** *blast*

have ε*(1+1/ε) = 1+ε
by (*smt* (*verit*) ε *add-divide-eq-if-simps*(*1*) *divide-cancel-right divide-self-if nonzero-mult-div-cancel-left*)
then have ∗: *9.84* ∗ ε^*2*(*1+1/ε*)^*2* / *2* = *9.84* ∗ (*1+ε*)^*2* / *2*
by (*metis* (*mono-tags*, *opaque-lifting*) *more-arith-simps*(*11*) *power-mult-distrib*)

have ε^*2* ∗ μ *mstar* ≥ ε^*2* ∗ *pivot* / *2*
using *lo-mu-star*
by (*metis less-eq-real-def ordered-comm-semiring-class.comm-mult-left-mono times-divide-eq-right zero-le-power2*)
then have ∗∗: ε^*2* ∗ μ *mstar* ≥ *9.84* ∗ (*1+ε*)^*2* / *2*
unfolding *pivot-def* **using** ∗ **by** *auto*

from *analysis-1-1*[*OF p ind mstar*]
have *measure-pmf.prob p*
{*s*. | *card-slice* ((λ*w*. *H w s*)) *mstar* − μ *mstar* | ≥ ε / (*1* + ε) ∗ μ *mstar* }
≤ (*1* + ε)^*2* / (ε^*2* ∗ μ *mstar*)
by *auto*
also have ... ≤ (*1* + ε)^*2* / (*9.84* ∗ (*1+ε*)^*2* / *2*)
using ∗∗
by (*smt* (*verit*) *divide-cancel-left divide-le-0-iff frac-le pos-prod-le power2-less-0 zero-eq-power2*)
also have ... = (*1* + ε)^*2* / (*4.92* ∗ (*1+ε*)^*2*)
by *simp*
also have ... = *1* / *4.92*
using ε **by** *simp*
finally have ∗∗∗∗∗∗∗: *measure-pmf.prob p*
{*s*. | *card-slice* ((λ*w*. *H w s*)) *mstar* − μ *mstar* | ≥ ε / (*1* + ε) ∗ μ *mstar* }
≤ *1* / *4.92* .

have μ *mstar* / (*1* + ε) − μ *mstar* = μ *mstar* ∗ (*1* / (*1+ε*) − *1*)
by (*simp add*: *right-diff-distrib'*)
also have ... = μ *mstar* ∗ (− ε / (*1+ε*))
by (*smt* (*verit*) ε *add-divide-distrib div-self minus-divide-left*)
finally have ∗∗∗: μ *mstar* / (*1* + ε) − μ *mstar* = μ *mstar* ∗ (− ε / (*1+ε*)) .

have {*h*. *real* (*card-slice h mstar*) ≤ μ *mstar* / (*1* + ε)}
= {*h*. *real* (*card-slice h mstar*) − μ *mstar* ≤ μ *mstar* / (*1* + ε)

$-\ \mu\ mstar\}$
by *auto*
also have $... = \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \leq \mu\ mstar * (-\ \varepsilon\ /\ (1+\varepsilon))\}$
using $***$ **by** *auto*
finally have $****$:
$\{h.\ real\ (card\text{-}slice\ h\ mstar) \leq \mu\ mstar\ /\ (1\ +\ \varepsilon)\} =$
$\{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \leq \mu\ mstar * (-\ \varepsilon\ /\ (1+\varepsilon))\}$ **.**

have *L mstar*
$= \{h.\ real\ (card\text{-}slice\ h\ mstar) < \mu\ mstar\ /\ (1\ +\ \varepsilon)\}$
unfolding *L-def* **by** *auto*
also have $...\subseteq \{h.\ real\ (card\text{-}slice\ h\ mstar) \leq \mu\ mstar\ /\ (1\ +\ \varepsilon)\}$
by *auto*
also have $... = \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \leq \mu\ mstar * (-\ \varepsilon\ /\ (1+\varepsilon))\}$
unfolding $****$ **by** *auto*
finally have *extend-L*: $L\ mstar \subseteq \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \leq \mu\ mstar * (-\ \varepsilon\ /\ (1+\varepsilon))\}$ **.**

have $*****$: $\mu\ mstar * (1\ +\ \varepsilon\ /\ (1+\varepsilon)) - \mu\ mstar = \mu\ mstar * (\varepsilon\ /\ (1+\varepsilon))$
by (*metis* (*no-types*, *opaque-lifting*) *add.commute diff-add-cancel group-cancel.sub1 mult.right-neutral right-diff-distrib'*)

have $******$: $U\ mstar = \{h.\ real\ (card\text{-}slice\ h\ mstar) \geq \mu\ mstar * (1\ +\ \varepsilon\ /\ (1+\varepsilon))\}$
unfolding *U-def* **by** *auto*
have $\{h.\ real\ (card\text{-}slice\ h\ mstar) \geq \mu\ mstar * (1\ +\ \varepsilon\ /\ (1+\varepsilon))\}$
$= \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \geq \mu\ mstar * (1\ +\ \varepsilon\ /\ (1+\varepsilon)) - \mu\ mstar\}$
by *auto*
also have $... = \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \geq \mu\ mstar * (\varepsilon\ /\ (1+\varepsilon))\}$
unfolding $*****$ **by** *auto*
finally have *extend-U*: $U\ mstar = \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \geq \mu\ mstar * (\varepsilon\ /\ (1+\varepsilon))\}$
using $******$ **by** *auto*

have $L\ mstar \cup U\ mstar \subseteq$
$\{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \leq \mu\ mstar * (-\ \varepsilon\ /\ (1+\varepsilon))\}$
$\cup \{h.\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar \geq \mu\ mstar * (\varepsilon\ /\ (1+\varepsilon))\}$
unfolding *extend-U*
using *extend-L*
by *auto*
also have $... = \{h.\ |\ real\ (card\text{-}slice\ h\ mstar) - \mu\ mstar\ | \geq \mu$

mstar ∗ (ε / (1+ε))}
by *auto*
finally have *extend-LU*: *L mstar* ∪ *U mstar* ⊆ {*h*. | *real* (*card-slice h mstar*) − μ *mstar* | ≥ μ *mstar* ∗ (ε / (1+ε))} **.**

have *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
≤ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) {*h*. | *real* (*card-slice h mstar*) − μ *mstar* | ≥ μ *mstar* ∗ (ε / (1+ε))}
using *extend-LU*
by (*auto intro*!: *measure-pmf.finite-measure-mono*)
also have ... = *measure-pmf.prob p*
{*s*. | *real* (*card-slice* (λ*w*. *H w s*) *mstar*) − μ *mstar* | ≥ ε / (1 + ε) ∗ μ *mstar* }
by (*simp add*: *mult.commute*)
also have ... ≤ *1* / *4.92*
using ∗∗∗∗∗∗∗ **by** *auto*
finally have *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*) ≤ *1* / *4.92* **.**
}

ultimately show *?thesis* **by** *auto*
qed

lemma *analysis-3*:
assumes *p*: *finite* (*set-pmf p*)
assumes *ind*: *prob-space.k-universal* (*measure-pmf p*) *2 H*
{α::'*a assg*. *dom* α = *S*}
{α::*nat assg*. *dom* α = {*0*..<*card S* − *1*}}
assumes ε*-up*: ε ≤ *1*
shows
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*)
approxcore-fail ≤ *0.36*
proof −
have *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) *approxcore-fail*
≤ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*)
(*T* (*mstar*−*3*) ∪
L (*mstar*−*2*) ∪
L (*mstar*−*1*) ∪
(*L mstar* ∪ *U mstar*))
using *failure-bound*
by (*auto intro*!: *measure-pmf.finite-measure-mono*)

moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*) ∪ *L* (*mstar*−*2*) ∪ *L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)

by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)
moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*) ∪ *L* (*mstar*−*2*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)
moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*2*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)
moreover have ... ≤ *1/62.5* + *1/20.68* + *1/10.84* + *1/4.92*
using *analysis-2-1*[*OF p ind ε-up*]
using *analysis-2-2*[*OF p ind*]
using *analysis-2-3*[*OF p ind*]
using *analysis-2-4*[*OF p ind*]
by *auto*
ultimately show *?thesis* **by** *force*
qed

lemma *analysis-3′*:
assumes *p*: *finite* (*set-pmf p*)
assumes *ind*: *prob-space.k-universal* (*measure-pmf p*) *2 H*
{α::′*a assg*. *dom* α = *S*}
{α::*nat assg*. *dom* α = {*0*..<*card S* − *1*}}
shows
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*)
approxcore-fail ≤ *0.44*
proof −
have *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) *approxcore-fail*
≤ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*)
(*T* (*mstar*−*3*) ∪
L (*mstar*−*2*) ∪
L (*mstar*−*1*) ∪
(*L mstar* ∪ *U mstar*))
using *failure-bound*
by (*auto intro*!: *measure-pmf.finite-measure-mono*)

moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*) ∪ *L* (*mstar*−*2*) ∪ *L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)

moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*) ∪ *L* (*mstar*−*2*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)
moreover have ... ≤
measure-pmf.prob (*map-pmf* (λ*s w*. *H w s*) *p*) (*T* (*mstar*−*3*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*2*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L* (*mstar*−*1*))
+ *measure-pmf.prob* (*map-pmf* (λ*s w*. *H w s*) *p*) (*L mstar* ∪ *U mstar*)
by (*auto intro*!: *measure-pmf.finite-measure-subadditive*)
moreover have ... ≤ *1/10.84* + *1/20.68* + *1/10.84* + *1/4.92*
using *analysis-2-1'*[*OF p ind*]
using *analysis-2-2*[*OF p ind*]
using *analysis-2-3*[*OF p ind*]
using *analysis-2-4*[*OF p ind*]
by *auto*
ultimately show *?thesis* **by** *auto*
qed
end

end

end

6 ApproxMC definition and analysis

This section puts together preceding results to formalize the PAC guarantee of ApproxMC.

theory *ApproxMCAnalysis* **imports**
ApproxMCCoreAnalysis
RandomXORHashFamily
Median-Method.Median
begin

lemma *replicate-pmf-Pi-pmf*:
assumes *distinct ls*
shows *replicate-pmf* (*length ls*) *P* =
map-pmf (λ*f*. *map f ls*)
(*Pi-pmf* (*set ls*) *def* (λ-. *P*))
using *assms*
proof (*induction ls*)
case *Nil*
then show *?case*
by *auto*

next
case (*Cons x xs*)
then show *?case*
by (*auto intro*!: *bind-pmf-cong simp add*: *Pi-pmf-insert' map-bind-pmf bind-map-pmf*)
qed

lemma *replicate-pmf-Pi-pmf'*:
assumes *finite V*
shows *replicate-pmf* (*card V*) *P* =
map-pmf (λ*f*. *map f* (*sorted-list-of-set V*))
(*Pi-pmf V def* (λ-. *P*))
proof −
have ∗:*card V* = *length* (*sorted-list-of-set V*)
using *assms* **by** *auto*
show *?thesis*
unfolding ∗
apply (*subst replicate-pmf-Pi-pmf*)
using *assms* **by** *auto*
qed

definition *map-of-default*::('*a* × '*b*) *list* ⇒ '*b* ⇒ '*a* ⇒ '*b*
where *map-of-default ls def* =
(*let m* = *map-of ls in*
(λ*x*. *case m x of None* ⇒ *def* | *Some v* ⇒ *v*))

lemma *Pi-pmf-replicate-pmf*:
assumes *finite V*
shows
(*Pi-pmf V def* (λ-. *p*)) =
map-pmf (λ*bs*.
map-of-default (*zip* (*sorted-list-of-set V*) *bs*) *def*)
(*replicate-pmf* (*card V*) *p*)
proof −
show *?thesis*
apply (*subst replicate-pmf-Pi-pmf'*[*OF assms*, **where** *def*=*def*])
unfolding *map-pmf-comp*
apply (*intro map-pmf-idI*[*symmetric*])
unfolding *map-of-default-def Let-def fun-eq-iff map-of-zip-map*
by (*smt* (*verit*, *del-insts*) *assms option.case*(*1*) *option.case*(*2*) *pmf-Pi pmf-eq-0-set-pmf sorted-list-of-set.set-sorted-key-list-of-set*)
qed

lemma *proj-inter-neutral*:
assumes ⋀*w*. *w* ∈ *B* ⟷ *restr S w* ∈ *C*
shows *proj S* (*A* ∩ *B*) = *proj S A* ∩ *C*
unfolding *ApproxMCCore.proj-def*
using *assms* **by** *auto*

An abstract spec of ApproxMC for any Boolean theory. This lo-

cale must be instantiated with a theory implementing the two the functions below (and satisfying the assumption linking them).

```
locale ApproxMC =
  fixes sols :: 'fml ⇒ ('a ⇒ bool) set
  fixes enc-xor :: 'a set × bool ⇒ 'fml ⇒ 'fml
  assumes sols-enc-xor:
    ⋀F xor. finite (fst xor) ⟹
      sols (enc-xor xor F) =
      sols F ∩ {ω. satisfies-xor xor {x. ω x}}
begin

definition compute-thresh :: real ⇒ nat
  where compute-thresh ε =
  nat ⌈1 + 9.84 * (1 + ε / (1 + ε)) * (1 + 1 / ε)^2⌉

definition fix-t :: real ⇒ nat
  where fix-t δ =
  nat ⌈ln (1 / δ) /(2 * (0.5−0.36)^2)⌉

definition raw-median-bound :: real ⇒ nat ⇒ real
  where raw-median-bound α t =
  (∑ i = 0..t div 2.
    (t choose i) * (1 / 2 + α) ^ i * (1 / 2 − α) ^ (t − i))

definition compute-t :: real ⇒ nat ⇒ nat
  where compute-t δ n =
  (if raw-median-bound 0.14 n < δ then n
  else fix-t δ)


definition size-xor ::
  'fml ⇒ 'a set ⇒
  (nat ⇒ ('a set × bool) option) ⇒
  nat ⇒ nat
  where size-xor F S xorsf i = (
    let xors = map (the ∘ xorsf) [0..<i] in
    let Fenc = fold enc-xor xors F in
      card (proj S (sols Fenc))
    )

definition check-xor ::
  'fml ⇒ 'a set ⇒
  nat ⇒
  (nat ⇒ ('a set × bool) option) ⇒
  nat ⇒ bool
  where check-xor F S thresh xorsf i =
  (size-xor F S xorsf i < thresh)

definition approxcore-xors ::
```

```
  'fml ⇒ 'a set ⇒
  nat ⇒
  (nat ⇒ ('a set × bool) option) ⇒
  nat
  where
    approxcore-xors F S thresh xorsf =
    (case List.find
      (check-xor F S thresh xorsf) [1..<card S] of
      None ⇒ 2 ^ card S
    | Some m ⇒
      (2 ^ m * size-xor F S xorsf m))

definition approxmccore :: 'fml ⇒ 'a set ⇒ nat ⇒ nat pmf
where approxmccore F S thresh =
  map-pmf (approxcore-xors F S thresh) (random-xors S (card S − 1))

definition approxmc :: 'fml ⇒ 'a set ⇒ real ⇒ real ⇒ nat ⇒ nat
pmf
  where approxmc F S ε δ n = (
    let thresh = compute-thresh ε in
    if card (proj S (sols F)) < thresh then
      return-pmf (card (proj S (sols F)))
    else
      let t = compute-t δ n in
      map-pmf (median t)
        (prod-pmf {0..<t::nat} (λi. approxmccore F S thresh))
  )

lemma median-commute:
  assumes t ≥ 1
  shows (real ∘ median t) = (λw::nat ⇒ nat. median t (real ∘ w))
  unfolding median-def map-map[symmetric]
  apply (subst Median.map-sort[where f = λx. real x])
  subgoal by (clarsimp simp add:mono-def)
  apply (subst nth-map)
  using assms by auto

lemma median-default:
  shows median t y = median t (λx. if x < t then y x else def)
  unfolding median-def
  by (auto intro!: arg-cong[where f = λls. sort ls ! (t div 2)])

definition default-α::'a set ⇒ nat assg
  where default-α S i = (if i < card S − 1 then Some True else None)

lemma dom-default-α:
  dom (default-α S) = {0..<card S −1}
  by (auto simp add:default-α-def split: if-splits)
```

lemma *compute-thresh-bound-4*:
assumes $\varepsilon > 0$
shows $4 <$ *compute-thresh* ε
proof −
have *1*: $(1 + \varepsilon \;/\; (1 + \varepsilon)) > 1$
using *assms*
by *simp*
have *2*: $(1 + 1 \;/\; \varepsilon)\hat{}2 > 1$
using *assms* **by** *simp*

define a **where** $a = (1 + \varepsilon \;/\; (1 + \varepsilon)) * (1 + 1 \;/\; \varepsilon)^2$
have $a > 1$ **unfolding** *a-def*
using *1 2*
using *less-1-mult* **by** *blast*
then have $(984 \;/\; 10^2) * a \geq 4$
by *auto*

thus *?thesis*
unfolding *compute-thresh-def*
by (*smt* (*verit*) *a-def arith-special*(*2*) *arithmetic-simps*(*1*) *more-arith-simps*(*11*) *nat-less-real-le numeral-Bit0 of-nat-numeral real-nat-ceiling-ge*)
qed

lemma *satisfies-xor-with-domain*:
assumes *fst* $x \subseteq S$
shows *satisfies-xor* x $\{x.\ w\ x\} \longleftrightarrow$
satisfies-xor x $(\{x.\ w\ x\} \cap S)$
using *assms*
apply (*cases* x)
by (*simp add*: *Int-assoc inf.absorb-iff2*)

lemma *approxcore-xors-eq*:
assumes *thresh*:
thresh = *compute-thresh* ε
thresh $\leq$ *card* (*proj* S (*sols* F))
assumes ε: $\varepsilon > (0::real)$ $\varepsilon \leq 1$
assumes S: *finite* S
shows *measure-pmf.prob* (*random-xors* S (*card* $S - 1$))
$\{xors.\ real\ (approxcore\text{-}xors\ F\ S\ thresh\ xors) \in$
$\{real\ (card\ (proj\ S\ (sols\ F))) \;/\; (1 + \varepsilon)..$
$(1 + \varepsilon) * real\ (card\ (proj\ S\ (sols\ F)))\}\} \geq 0.64$
proof −

have *ApproxMCCore* (*sols* F) S ε (*default-*α S) *thresh*
apply *unfold-locales*
subgoal using *dom-default-*α **by** *simp*
subgoal using ε **by** *simp*
subgoal using *thresh assms*(*3*) *compute-thresh-bound-4* **by** *blast*

```
  using thresh S by auto
 then interpret amc: ApproxMCCore sols F - - (default-α S) .

 have
   m < card S ⟹
   {0..<m} ⊆ dom xors ⟹
   (⋀i. i < m ⟹ fst (the (xors i)) ⊆ S) ⟹
   (proj S
      (sols (fold enc-xor (map (the ∘ xors) [0..<m]) F))) =
    proj S (sols F) ∩
      {w. hslice m (λω. xor-hash ω xors) w =
        aslice m (default-α S)} for m xors
 proof (induction m)
   case 0
   then show ?case
     unfolding hslice-def aslice-def
     by auto
 next
   case (Suc m)
   have m: m ∈ dom xors
     by (meson Set.basic-monos(7) Suc(3) atLeastLessThan-iff le0
lessI)
   have sp: fst (the (xors m)) ⊆ S
     by (simp add: Suc(4))

   then obtain xor where x: xors m = Some xor
     using m by blast

   have eq: {w. xor-hash w xors m = Some True} =
      {ω. satisfies-xor xor {x. ω x = Some True}}
     unfolding xor-hash-def
     by (clarsimp simp add: x)

   have neut: ⋀w.
     w ∈ {ω. satisfies-xor xor {x. ω x}} ⟷
     restr S w ∈ {ω. satisfies-xor xor {x. ω x = Some True}}
     using sp unfolding restr-def
      by (smt (verit, ccfv-SIG) Collect-cong Int-def mem-Collect-eq
option.sel satisfies-xor-with-domain x)

   have lhs:
     proj S
      (sols (fold enc-xor (map (the ∘ xors) [0..<Suc m]) F)) =
     proj S (sols (fold enc-xor (map (the ∘ xors) [0..<m]) F)) ∩
       {w. xor-hash w xors m = Some True}
     apply clarsimp
     apply (subst sols-enc-xor)
     subgoal using assms(5) rev-finite-subset sp by blast
     apply (subst proj-inter-neutral)
```

using *eq neut x* **by** *auto*

have *rhs1*: *hslice* (*Suc m*) (λω. *xor-hash* ω *xors*) *w* = *aslice* (*Suc m*) (*default-α S*) ⟹
hslice m (λω. *xor-hash* ω *xors*) *w* = *aslice m* (*default-α S*) **for** *w*
unfolding *hslice-def aslice-def fun-eq-iff*
by (*auto simp add*:*lessThan-Suc restrict-map-def split*: *if-splits*)

have *rhs2*:*hslice* (*Suc m*) (λω. *xor-hash* ω *xors*) *w* = *aslice* (*Suc m*) (*default-α S*) ⟹
xor-hash w xors m = *Some True* **for** *w*
unfolding *hslice-def aslice-def fun-eq-iff*
apply (*clarsimp simp add*:*lessThan-Suc restrict-map-def*)
by (*metis default-α-def domIff m xor-hash-eq-dom*)

have *rhs3*: *hslice m* (λω. *xor-hash* ω *xors*) *w* = *aslice m* (*default-α S*) ⟹
xor-hash w xors m = *Some True* ⟹
hslice (*Suc m*) (λω. *xor-hash* ω *xors*) *w* = *aslice* (*Suc m*) (*default-α S*) **for** *w*
unfolding *hslice-def aslice-def fun-eq-iff*
apply (*clarsimp simp add*:*lessThan-Suc restrict-map-def*)
by (*metis One-nat-def Suc.prems*(*1*) *Suc-lessD Suc-less-eq Suc-pred default-α-def gr-zeroI zero-less-diff*)

have *rhs*: {*w*. *hslice* (*Suc m*) (λω. *xor-hash* ω *xors*) *w* = *aslice* (*Suc m*) (*default-α S*)} =
{*w*. *hslice m* (λω. *xor-hash* ω *xors*) *w* = *aslice m* (*default-α S*)}
∩
{*w*. *xor-hash w xors m* = *Some True*}
by (*auto simp add*: *rhs1 rhs2 rhs3*)

have *ih*: *proj S* (*sols* (*fold enc-xor* (*map* (*the* ∘ *xors*) [*0*..<*m*]) *F*)) =
proj S (*sols F*) ∩
{*w*. *hslice m* (λω. *xor-hash* ω *xors*) *w* = *aslice m* (*default-α S*)}
apply (*intro Suc*(*1*))
using *Suc*(*2*) *Suc-lessD* **apply** *blast*
using *Suc*(*3*) *atLeast0-lessThan-Suc* **apply** *blast*
using *Suc*(*4*) *less-SucI* **by** *blast*

show *?case*
unfolding *lhs rhs*
by (*simp add*: *Int-ac*(*1*) *ih*)
qed
then have ∗:
m < *card S* ⟹
{*0*..<*m*} ⊆ *dom xors* ⟹
(⋀*i*. *i* < *m* ⟹ *fst* (*the* (*xors i*)) ⊆ *S*) ⟹

```
    size-xor F S xors m =
    amc.card-slice (λω. xor-hash ω xors) m for m xors
   unfolding size-xor-def amc.card-slice-def
   by auto

  have **:
   {0..<card S − 1} ⊆ dom xors ⟹
   (⋀i. i < card S − 1 ⟹ fst (the (xors i)) ⊆ S) ⟹
   find (check-xor F S thresh xors) [1..<card S] =
   find (λi. (λω. xor-hash ω xors) ∈ amc.T i) [1..<card S] for xors
    apply (intro find-cong)
    unfolding check-xor-def amc.T-def
    subgoal by simp
    apply (subst *)
     subgoal by clarsimp
     subgoal by (clarsimp simp add: domIff subset-iff)
   by auto

  have rw:
    {0..<card S − 1} ⊆ dom xors ⟹
    (⋀i. i < card S − 1 ⟹ fst (the (xors i)) ⊆ S) ⟹
    approxcore-xors F S thresh xors =
      (λ(a,b). a*b) (amc.approxcore (λω. xor-hash ω xors)) for  xors
    apply (subst amc.approxcore-def)
    unfolding approxcore-xors-def
    apply (subst **)
     subgoal by clarsimp
     subgoal by clarsimp
    apply (clarsimp split: option.split)
    apply (subst *)
    subgoal by (auto simp add: find-Some-iff domIff subset-iff)
    subgoal by (auto simp add: find-Some-iff domIff subset-iff)
    subgoal
      using ‹⋀x2. ⟦{0..<card S − Suc 0} ⊆ dom xors; ⋀i. i < card
S − Suc 0 ⟹ fst (the (xors i)) ⊆ S; find (λi. (λω. xor-hash ω xors)
∈ amc.T i) [Suc 0..<card S] = Some x2⟧ ⟹ x2 < card S› by auto
    by auto

  from xor-hash-family-2-universal[OF S]
  have univ:prob-space.k-universal (measure-pmf (random-xors S (card
S − 1))) 2
   xor-hash {α. dom α = S} {α. dom α = {0..<card S − 1}} .

  have measure-pmf.prob
   (map-pmf (λs w. xor-hash w s) (random-xors S (card S − 1)))
   amc.approxcore-fail ≤ 0.36
    apply (intro amc.analysis-3[OF - - univ])
     apply (smt (verit, ccfv-SIG) Groups.mult-ac(3) amc.pivot-def
assms(1) compute-thresh-def more-arith-simps(11) real-nat-ceiling-ge)
```

```
    using S finite-random-xors-set-pmf apply blast
    using ε by auto

  then have b: measure-pmf.prob
    (random-xors S (card S − 1))
    {xors.
      (real ((λ(a,b). a∗b) (amc.approxcore (λω. xor-hash ω xors))))
      ∉
      {real (card (proj S (sols F))) / (1 + ε)..
        (1 + ε) ∗ real (card (proj S (sols F)))}} ≤ 0.36
    unfolding amc.approxcore-fail-def
    by (auto simp add: case-prod-unfold Let-def)

  have 1: x ∈ set-pmf (random-xors S (card S − Suc 0)) ⟹
    {0..<card S − 1} ⊆ dom x for x
    by (auto simp add:random-xors-set-pmf[OF S])
  have 2: x ∈ set-pmf (random-xors S (card S − Suc 0)) ⟹
    (∀ i. i < card S − 1 ⟶ fst (the (x i)) ⊆ S) for x
  proof −
    assume x: x ∈ set-pmf (random-xors S (card S − Suc 0))
    moreover {
      fix i
      assume i: i < card S − 1
      from random-xors-set-pmf[OF S]
       have xx: dom x = {..<(card S − Suc 0)} ran x ⊆ Pow S ×
UNIV
        using x by auto
      obtain xi where xi: x i = Some xi
        using xx i apply clarsimp
      by (metis atLeast0LessThan atLeastLessThan-iff bot-nat-0.extremum
domIff option.exhaust surj-pair)
      then have fst xi ⊆ S using xx(2)
        unfolding ran-def apply (clarsimp simp add: subset-iff)
        by (metis prod.collapse)
      then have fst (the (x i)) ⊆ S by (simp add: xi)
    }
    thus (∀ i. i < card S − 1 ⟶ fst (the (x i)) ⊆ S) by auto
  qed

  have measure-pmf.prob (random-xors S (card S − 1))
      {xors. real (approxcore-xors F S thresh xors) ∈
       {real (card (proj S (sols F))) / (1 + ε)..
       (1 + ε) ∗ real (card (proj S (sols F)))}} =
    measure-pmf.prob
    (random-xors S (card S − 1))
    {xors.
      (real ((λ(a,b). a∗b) (amc.approxcore (λω. xor-hash ω xors))))
      ∈
      {real (card (proj S (sols F))) / (1 + ε)..
```

```
      (1 + ε) * real (card (proj S (sols F)))}}
  apply (intro measure-pmf.measure-pmf-eq[where p = (random-xors
S (card S - 1))])
   subgoal by auto
   apply clarsimp
   apply (frule 1)
   apply (drule 2)
   apply (frule rw)
   by auto

 moreover have ... =
    1 - measure-pmf.prob
     (random-xors S (card S - 1))
     {xors.
       (real ((λ(a,b). a*b) (amc.approxcore (λω. xor-hash ω xors))))
       ∉
       {real (card (proj S (sols F))) / (1 + ε)..
         (1 + ε) * real (card (proj S (sols F)))}}
   apply (subst measure-pmf.prob-compl[symmetric])
   by (auto intro!: measure-pmf.measure-pmf-eq)
 moreover have ... ≥ 0.64
   using b
   by auto
 ultimately show ?thesis by auto
qed

lemma compute-t-ge1:
 assumes 0 < δ δ < 1
 shows compute-t δ n ≥ 1
proof -
 have ln (1 / δ) > 0
   by (simp add: assms)
 then have fix-t: 1 ≤ fix-t δ
   unfolding fix-t-def
   by (simp add: Suc-leI)

 show ?thesis
 unfolding compute-t-def
 using fix-t
 apply (cases n)
 unfolding raw-median-bound-def
 using assms by auto
qed

lemma success-arith-bound:
 assumes s ≤ (f ::nat)
 assumes p ≤ (1::real) q ≤ p 1 /2 ≤ q
 shows p ^ s * (1 - p) ^ f ≤ q ^ s * (1 - q) ^ f
proof -
```

```
  have ple: p * (1−p) ≤ q * (1−q)
    using assms(2−4)
     by (sos (((A<0 * R<1) + ((R<1 * (R<1 * [p + ~1*q]^2)) +
((A<=1 * (A<=2 * R<1)) * (R<2 * [1]^2))))))

  have feq:f = (f−s)+s
    using Nat.le-imp-diff-is-add assms(1) by blast
  then have (1−p)^f = (1−p)^s * (1−p)^(f−s)
    by (metis add.commute power-add)
  then have p ^ s * (1 − p) ^ f =
    (p * (1−p)) ^ s * (1 − p) ^ (f−s)
    by (simp add: power-mult-distrib)
  moreover have ... ≤
    (q * (1−q)) ^ s * (1 − p) ^ (f−s)
   by (smt (verit) assms(1) assms(2) assms(3) assms(4) diff-self-eq-0
divide-nonneg-nonneg mult-nonneg-nonneg mult-right-mono order-le-less
ple power-0 power-eq-0-iff power-mono zero-less-diff zero-less-power)
  moreover have ... ≤
    (q * (1−q)) ^ s * (1 − q) ^ (f−s)
   by (smt (verit, ccfv-SIG) assms(2) assms(3) assms(4) divide-eq-0-iff
divide-nonneg-nonneg mult-left-mono mult-pos-pos power-mono zero-less-power)
  moreover have ... = q ^ s * (1 − q) ^ f
   by (smt (verit) feq mult.assoc mult.commute power-add power-mult-distrib)
  ultimately show ?thesis by auto
qed

lemma prob-binomial-pmf-upto-mono:
  assumes 1/2 ≤ q q ≤ p p ≤ 1
  shows
  measure-pmf.prob (binomial-pmf n p) {..n div 2} ≤
  measure-pmf.prob (binomial-pmf n q) {..n div 2}
proof −
  have i: i ≤ n div 2 ⟹
    p ^ i * (1 − p) ^ (n − i) ≤ q ^ i * (1 − q) ^ (n − i) for i
    using assms by(auto intro!: success-arith-bound)

  show ?thesis
    apply (subst prob-binomial-pmf-upto)
    subgoal using assms by auto
    subgoal using assms by auto
    apply (subst prob-binomial-pmf-upto)
    subgoal using assms by auto
    subgoal using assms by auto
   by (auto intro!: sum-mono simp add: i ab-semigroup-mult-class.mult-ac(1)
mult-left-mono)
qed


theorem approxmc-sound:
```

```
  assumes δ: δ > 0 δ < 1
  assumes ε: ε > 0 ε ≤ 1
  assumes S: finite S
  shows measure-pmf.prob (approxmc F S ε δ n)
      {c. real c ∈
        {real (card (proj S (sols F))) / (1 + ε)..
          (1 + ε) * real (card (proj S (sols F)))}}
      ≥ 1 − δ
proof −
  define thresh where thresh = compute-thresh ε
  define t where t = compute-t δ n
  then have t1: 1 ≤ t
    using compute-t-ge1[OF δ] by auto

  have card (proj S (sols F)) < thresh ∨
      card (proj S (sols F)) ≥ thresh by auto
  moreover {
    assume card (proj S (sols F)) < thresh
    then have approxmc F S ε δ n =
      return-pmf (card (proj S (sols F)))
      unfolding approxmc-def Let-def thresh-def
      by auto
    then have ?thesis
      unfolding indicator-def of-bool-def
      using assms ε
       by (auto simp add: mult-le-cancel-left1 mult-le-cancel-right1 di-
vide-le-eq)
  }
  moreover {
    assume a: card (proj S (sols F)) ≥ thresh
    define Xf where Xf = (λ(i::nat) xs.
      approxcore-xors F S thresh (xs i))

    then have ∗: approxmc F S ε δ n =
      map-pmf (median t)
      (prod-pmf {0..<t} (λi. approxmccore F S thresh))
      using a
      unfolding approxmc-def Let-def thresh-def t-def
      by auto

    have ∗∗: map-pmf (real ∘ median t)
      (Pi-pmf {0..<t} (approxcore-xors F S thresh undefined)
       (λi. approxmccore F S thresh)) =
       map-pmf (λω. median t (λi. real (Xf i ω)))
      (prod-pmf {0..<t} (λi. random-xors S (card S − 1)))
      apply (subst median-commute)
      subgoal using t1 by simp
      unfolding approxmccore-def
       apply (subst Pi-pmf-map)
```

```
  unfolding Xf-def by (auto simp add: pmf.map-comp o-def)

 define α where α = (0.14 ::real)
 then have α: α > 0 by auto

 have indep:prob-space.indep-vars
  (measure-pmf
    (prod-pmf {0..<t} (λi. random-xors S (card S − 1))))
   (λ-. borel) (λx xa. real (Xf x xa)) {0..<t}
   unfolding Xf-def
   apply (intro indep-vars-restrict-intro′)
   by (auto simp add: restrict-dfl-def)

 have d: δ ∈ {0<..<1} using δ by auto

 from approxcore-xors-eq[OF thresh-def a ε S]
 have b1: 1 / 2 + α ≤
  measure-pmf.prob (random-xors S (card S − 1))
   {xors.
    real (approxcore-xors F S thresh xors)
    ∈ {real (card (proj S (sols F))) /
       (1 + ε)..(1 + ε) ∗ real (card (proj S (sols F)))}}
   unfolding α-def by auto
 then have b2: i < t ⟹
   1 / 2 + α ≤
   measure-pmf.prob
     (prod-pmf {0..<t}
       (λi. random-xors S (card S − 1)))
     {ω ∈ space
           (measure-pmf
             (prod-pmf {0..<t}
               (λi. random-xors S (card S − 1)))).
      real (Xf i ω)
      ∈ {real (card (proj S (sols F))) /(1 + ε)..
         (1 + ε) ∗real (card (proj S (sols F)))}} for i
 unfolding Xf-def apply clarsimp
 apply (subst prob-prod-pmf-slice)
 by auto

 have ∗∗∗: 1 − δ
   ≤ measure-pmf.prob (prod-pmf {0..<t} (λi. random-xors S (card
S − 1)))
   {ω.
    median t (λi. real (Xf i ω))
    ∈ {real (card (proj S (sols F))) /
       (1 + ε)..(1 + ε) ∗ real (card (proj S (sols F)))}}
 proof −
   have t = fix-t δ ∨ t = n ∧ raw-median-bound α n < δ
   unfolding t-def compute-t-def α-def by auto
```

```
    moreover {
      assume t = fix-t δ
      then have tb:- ln δ / (2 * α^2) ≤ real t
      unfolding fix-t-def α-def
      apply clarsimp
     by (metis assms(1) divide-minus-left inverse-eq-divide ln-inverse
real-nat-ceiling-ge)

      from measure-pmf.median-bound-1[OF α d indep tb]
      have ?thesis using b2 by auto
    }
    moreover {
      assume *: t = n raw-median-bound α n < δ
      have s: 1 / 2 - α = 1 - (1 /2 + α)
        by auto

      have d1: 0 < t using t1 by linarith
      have d2: 1 / 2 + α ≥ 0 using α by auto
      have d3: interval{x..y::real} for x y
        unfolding interval-def by auto

      from prob-space.median-bound-raw[OF - d1 d2 d3 indep b2]
      have 1 -
        measure-pmf.prob (binomial-pmf t (1 / 2 + α)) {..t div 2}
        ≤ measure-pmf.prob
            (prod-pmf {0..<t}
              (λi. random-xors S (card S - 1)))
            {ω.
             median t (λi. real (Xf i ω))
             ∈ {real (card (proj S (sols F))) /
                 (1 + ε)..(1 + ε) * real (card (proj S (sols F)))}}
        by (auto simp add: prob-space-measure-pmf)

       moreover have measure-pmf.prob (binomial-pmf t (1 / 2 +
α)) {..t div 2} ≤ δ
          by (smt (verit, ccfv-SIG) * b1 d2 measure-pmf.prob-le-1
prob-binomial-pmf-upto raw-median-bound-def s sum.cong)

      ultimately have ?thesis by auto
    }
    ultimately show ?thesis by auto
  qed

  have measure-pmf.prob (approxmc F S ε δ n)
    {c. real c
      ∈ {real (card (proj S (sols F))) /
          (1 + ε)..(1 + ε) * real (card (proj S (sols F)))}} =
    measure-pmf.prob (map-pmf (real ∘ median t)
      (prod-pmf {0..<t}
```

```
      (λi. approxmccore F S thresh)))
       {c. c ∈ {real (card (proj S (sols F))) /
             (1 + ε)..(1 + ε) * real (card (proj S (sols F)))}}
    using * by auto
  moreover have ... =
    measure-pmf.prob (map-pmf (real ∘ median t)
    (map-pmf (λf x. if x ∈ {0..<t} then f x else undefined) (Pi-pmf
{0..<t} (approxcore-xors F S thresh undefined)
     (λi. approxmccore F S thresh))))
    {c. c ∈ {real (card (proj S (sols F))) /
          (1 + ε)..(1 + ε) * real (card (proj S (sols F)))}}
    apply (subst Pi-pmf-default-swap)
    by auto
  moreover have ... =
    measure-pmf.prob (map-pmf (real ∘ median t)
    (Pi-pmf {0..<t} (approxcore-xors F S thresh undefined)
     (λi. approxmccore F S thresh)))
    {c. c ∈ {real (card (proj S (sols F))) /
          (1 + ε)..(1 + ε) * real (card (proj S (sols F)))}}
    by (clarsimp simp add: median-default[symmetric])
  moreover have ... ≥ 1 − δ
    unfolding **
    using ***
    by auto
  ultimately have ?thesis by auto
 }
 ultimately show ?thesis by auto
qed
```

To simplify further analyses, we can remove the (required) upper bound on epsilon.

```
definition mk-eps :: real ⇒ real
 where mk-eps ε = (if ε > 1 then 1 else ε)

definition approxmc'::
 'fml ⇒ 'a set ⇒
 real ⇒ real ⇒ nat ⇒ nat pmf
 where approxmc' F S ε δ n =
   approxmc F S (mk-eps ε) δ n

corollary approxmc'-sound:
 assumes δ: δ > 0 δ < 1
 assumes ε: ε > 0
 assumes S: finite S
 shows prob-space.prob (approxmc' F S ε δ n)
    {c. real c ∈
     {real (card (proj S (sols F))) / (1 + ε)..
       (1 + ε) * real (card (proj S (sols F)))}}
    ≥ 1 − δ
```

```
proof −
  define ε′ where ε′ = (if ε > 1 then 1 else ε)
  have ε′: 0 < ε′ ε′ ≤ 1
    unfolding ε′-def using ε by auto

  from approxmc-sound[OF δ ε′ S]
  have ∗: prob-space.prob (approxmc F S ε′ δ n)
      {c. real c ∈
        {real (card (proj S (sols F))) / (1 + ε′)..
          (1 + ε′) ∗ real (card (proj S (sols F)))}}
      ≥ 1 − δ .

  have ∗∗:
    {c. real c ∈
        {real (card (proj S (sols F))) / (1 + ε′)..
          (1 + ε′) ∗ real (card (proj S (sols F)))}}
    ⊆
    {c. real c ∈
        {real (card (proj S (sols F))) / (1 + ε)..
          (1 + ε) ∗ real (card (proj S (sols F)))}}
    unfolding ε′-def
    apply clarsimp
    apply (rule conjI)
   apply (smt (verit) field-sum-of-halves frac-less2 zero-less-divide-iff)
   by (metis (no-types, opaque-lifting) add-le-cancel-left arith-special(3)
dual-order.trans less-eq-real-def mult-right-mono of-nat-0-le-iff)

  show ?thesis
    apply (intro order.trans[OF ∗])
    unfolding approxmc′-def ε′-def mk-eps-def
    apply (intro measure-pmf.finite-measure-mono)
    using ∗∗[unfolded ε′-def]
    by auto
qed
```

This shows we can lift all randomness to the top-level (i.e., eagerly sample it).

```
definition approxmc-map::
  'fml ⇒ 'a set ⇒
  real ⇒ real ⇒ nat ⇒
  (nat ⇒ nat ⇒ ('a set × bool) option) ⇒
  nat
  where approxmc-map F S ε δ n xorsFs = (
    let ε = mk-eps ε in
    let thresh = compute-thresh ε in
    if card (proj S (sols F)) < thresh then
      card (proj S (sols F))
    else
      let t = compute-t δ n in
```

median t (approxcore-xors F S thresh ∘ xorsFs))

lemma *approxmc-map-eq*:
shows
map-pmf (approxmc-map F S ε δ n)
(Pi-pmf {0..<compute-t δ n} def
(λi. random-xors S (card S − 1))) =
approxmc′ F S ε δ n
proof −
define *def′* **where** *def′ = approxcore-xors F S (compute-thresh (mk-eps ε)) def*

have ∗:
map-pmf (median (compute-t δ n))
(prod-pmf {0..<compute-t δ n}
(λi. map-pmf
(approxcore-xors F S
(compute-thresh (mk-eps ε)))
(random-xors S (card S − Suc 0)))) =
map-pmf (median (compute-t δ n))
(Pi-pmf {0..<compute-t δ n} def′
(λi. map-pmf
(approxcore-xors F S
(compute-thresh (mk-eps ε)))
(random-xors S (card S − Suc 0))))
apply (*subst Pi-pmf-default-swap*[*symmetric*, **where** *dflt =undefined*, **where** *dflt′=def′*])
by (*auto simp add*: *map-pmf-comp median-default*[*symmetric*])

show *?thesis*
unfolding *approxmc′-def approxmc-map-def approxmc-def Let-def approxmccore-def*
using *def′-def*
by (*auto simp add*: *map-pmf-comp Pi-pmf-map*[*of - - def*] ∗)
qed

end

end

7 Certificate-based ApproxMC

This turns the randomized algorithm into an executable certificate checker

theory *CertCheck*
imports *ApproxMCAnalysis*

begin

7.1 ApproxMC with lists instead of sets

type-synonym *'a xor = 'a list × bool*

definition *satisfies-xorL :: 'a xor ⇒ ('a ⇒ bool) ⇒ bool*
where *satisfies-xorL xb ω =*
even (sum-list (map (of-bool ∘ ω) (fst xb)) +
of-bool (snd xb)::nat)

definition *sublist-bits::'a list ⇒ bool list ⇒ 'a list*
where *sublist-bits ls bs =*
map fst (filter snd (zip ls bs))

definition *xor-from-bits::*
'a list ⇒ bool list × bool ⇒ 'a xor
where *xor-from-bits V xsb =*
(sublist-bits V (fst xsb), snd xsb)

locale *ApproxMCL =*
fixes *sols :: 'fml ⇒ ('a ⇒ bool) set*
fixes *enc-xor :: 'a xor ⇒ 'fml ⇒ 'fml*
assumes *sols-enc-xor:*
⋀F xor.
sols (enc-xor xor F) =
sols F ∩ {ω. satisfies-xorL xor ω}
begin

definition *list-of-set ::'a set ⇒ 'a list*
where *list-of-set x = (@ls. set ls = x ∧ distinct ls)*

definition *xor-conc :: 'a set × bool ⇒ 'a xor*
where *xor-conc xsb = (list-of-set (fst xsb), snd xsb)*

definition *enc-xor-conc :: 'a set × bool ⇒ 'fml ⇒ 'fml*
where *enc-xor-conc = enc-xor ∘ xor-conc*

lemma *distinct-count-list:*
assumes *distinct ls*
shows *count-list ls x = of-bool (x ∈ set ls)*
using *assms*
apply *(induction ls)*
by *auto*

lemma *list-of-set:*
assumes *finite x*
shows *distinct (list-of-set x) set (list-of-set x) = x*
unfolding *list-of-set-def*
by *(metis (mono-tags, lifting) assms finite-distinct-list someI-ex)+*

lemma *count-list-list-of-set*:
assumes *finite x*
shows *count-list* (*list-of-set x*) *y* = *of-bool* (*y* ∈ *x*)
apply (*subst distinct-count-list*)
using *list-of-set*[*OF assms*]
by *auto*

lemma *satisfies-xorL-xor-conc*:
assumes *finite x*
shows*satisfies-xorL* (*xor-conc* (*x*,*b*)) ω ⟷ *satisfies-xor* (*x*,*b*) {*x*. ω *x*}
unfolding *satisfies-xorL-def xor-conc-def*
using *list-of-set*[*OF assms*]
by (*auto simp add*: *sum-list-map-eq-sum-count count-list-list-of-set*[*OF assms*] *Int-ac*(*3*) *assms*)

sublocale *appmc*: *ApproxMC sols enc-xor-conc*
apply *unfold-locales*
unfolding *enc-xor-conc-def o-def*
apply (*subst sols-enc-xor*)
using *satisfies-xorL-xor-conc* **by** *fastforce*

definition *size-xorL* ::
'fml ⇒ *'a list* ⇒
(*nat* ⇒ *bool list* × *bool*) ⇒
nat ⇒ *nat*
where *size-xorL F S xorsl i* = (
let xors = *map* (*xor-from-bits S* ∘ *xorsl*) [*0*..<*i*] *in*
let Fenc = *fold enc-xor xors F in*
card (*proj* (*set S*) (*sols Fenc*)))

definition *check-xorL* ::
'fml ⇒ *'a list* ⇒
nat ⇒
(*nat* ⇒ *bool list* × *bool*) ⇒
nat ⇒ *bool*
where *check-xorL F S thresh xorsl i* =
(*size-xorL F S xorsl i* < *thresh*)

definition *approxcore-xorsL* ::
'fml ⇒ *'a list* ⇒
nat ⇒
(*nat* ⇒ (*bool list* × *bool*)) ⇒
nat
where
approxcore-xorsL F S thresh xorsl =
(*case List.find*
(*check-xorL F S thresh xorsl*) [*1*..<*length S*] *of*
None ⇒ *2* ^ *length S*

```
    | Some m ⇒
      (2 ^ m * size-xorL F S xorsl m))

definition xor-abs :: 'a xor ⇒ 'a set × bool
  where xor-abs xsb = (set (fst xsb), snd xsb)

lemma sols-fold-enc-xor:
  assumes list-all2 (λx y.
    ∀ w. satisfies-xorL x w = satisfies-xorL y w) xs ys
  assumes sols F = sols G
  shows sols (fold enc-xor xs F) = sols (fold enc-xor ys G)
  using assms
proof (induction xs arbitrary: ys F G)
  case Nil
  then show ?case
    by auto
  next
  case (Cons x xss)
  then obtain y yss where ys: ys = y#yss
  by (meson list-all2-Cons1)
  have all2: ∀ w. satisfies-xorL x w = satisfies-xorL y w
    using Cons.prems(1) ys by blast
  have *: sols (enc-xor x F) = sols (enc-xor y G)
    apply (subst sols-enc-xor)
    using all2 local.Cons(3) sols-enc-xor by presburger
  then show ?case unfolding ys
  using * Cons.IH Cons.prems(2) local.Cons(2) local.Cons(3) ys by
auto
qed

lemma satisfies-xor-xor-abs:
  assumes distinct x
  shows satisfies-xor (xor-abs (x,b)) {x. ω x} ⟷ satisfies-xorL (x,b)
ω
  unfolding satisfies-xorL-def xor-abs-def
  apply (clarsimp simp add: sum-list-map-eq-sum-count)
  by (smt (verit, ccfv-SIG) IntD1 Int-commute assms card-eq-sum dis-
tinct-count-list of-bool-eq(2) sum.cong)

lemma xor-conc-xor-abs-rel:
  assumes distinct (fst x)
  shows satisfies-xorL (xor-conc (xor-abs x)) w ⟷
    satisfies-xorL x w
  unfolding xor-abs-def
  apply (subst satisfies-xorL-xor-conc)
  subgoal by (simp add: xor-abs-def[symmetric])
  using assms satisfies-xor-xor-abs xor-abs-def by auto

lemma sorted-sublist-bits:
```

assumes *sorted V*
shows*sorted* (*sublist-bits V bs*)
unfolding *sublist-bits-def*
using *assms*
by (*auto intro*!: *sorted-filter sorted-wrt-take simp add*: *map-fst-zip-take*)

lemma *distinct-sublist-bits*:
assumes *distinct V*
shows*distinct* (*sublist-bits V bs*)
unfolding *sublist-bits-def*
using *assms*
by (*auto intro*!: *distinct-map-filter simp add*: *map-fst-zip-take*)

lemma *distinct-fst-xor-from-bits*:
assumes *distinct V*
shows*distinct* (*fst* (*xor-from-bits V bs*))
unfolding *xor-from-bits-def*
using *distinct-sublist-bits*[*OF assms*]
by *auto*

lemma *size-xorL*:
assumes $\bigwedge j.\ j < i \Longrightarrow$
xorsf j =
Some (*xor-abs* (*xor-from-bits S* (*xorsl j*)))
assumes *distinct S*
shows *size-xorL F S xorsl i* =
appmc.size-xor F (*set S*) *xorsf i*
unfolding *appmc.size-xor-def size-xorL-def*
apply (*clarsimp simp add*: *enc-xor-conc-def fold-map*[*symmetric*])
apply (*intro arg-cong*[**where** *f* = (λ*x*. *card* (*proj* (*set S*) *x*))])
apply (*intro sols-fold-enc-xor*)
by (*auto simp add*: *list-all2-map1 list-all2-map2 list-all2-same assms*(*1*)
assms(*2*) *distinct-fst-xor-from-bits xor-conc-xor-abs-rel*)

lemma *fold-enc-xor-more*:
assumes *x* ∈ *sols* (*fold enc-xor* (*xs* @ *rev ys*) *F*)
shows *x* ∈ *sols* (*fold enc-xor xs F*)
using *assms*
proof (*induction ys arbitrary*: *F*)
case *Nil*
then show *?case*
by *auto*
next
case *ih*: (*Cons y ys*)
show *?case*
using *ih* **by** (*auto simp add*: *ih.prems*(*1*) *sols-enc-xor*)
qed

lemma *size-xorL-anti-mono*:

assumes $x \leq y$ *distinct* S
shows *size-xorL* F S *xorsl* $x \geq$ *size-xorL* F S *xorsl* y
proof −
obtain *ys* **where** *ys*: $[0..<y] = [0..<x]$ @ *ys distinct ys*
by (*metis assms*(1) *bot-nat-0.extremum distinct-upt ordered-cancel-comm-monoid-diff-class.add-diff-inv upt-add-eq-append*)

define *rys* **where***rys* = (*rev* (*map* (*xor-from-bits* $S \circ$ *xorsl*) *ys*))
have ∗: $\bigwedge y.\ y \in$ *set rys* $\Longrightarrow$ *distinct* (*fst y*)
unfolding *rys-def*
using *assms*(2) *distinct-fst-xor-from-bits*
by (*metis* (*no-types*, *opaque-lifting*) *ex-map-conv o-apply set-rev*)

show *?thesis*
unfolding *size-xorL-def Let-def*
apply (*intro card-mono proj-mono*)
subgoal using *card-proj*(1) **by** *blast*
unfolding *ys*
by (*metis fold-enc-xor-more map-append rev-rev-ident subsetI*)
qed

lemma *find-upto-SomeI*:
assumes $\bigwedge i.\ a \leq i \Longrightarrow i < x \Longrightarrow \neg P\ i$
assumes $P\ x\ a \leq x\ x < b$
shows *find* P $[a..<b] =$ *Some* x
proof −
have x: $[a..<b]$! $(x-a) = x$
by (*simp add*: *assms*(3) *assms*(4))
have j: $\bigwedge j.\ j<x-a \Longrightarrow \neg\ P\ ([a..<b]\ !\ j)$
using *assms*(1) *assms*(4) **by** *auto*
show *?thesis*
unfolding *find-Some-iff*
using x j
by (*metis assms*(2) *assms*(3) *assms*(4) *diff-less-mono length-upt*)
qed

lemma *check-xorL*:
assumes $\bigwedge j.\ j < i \Longrightarrow$
xorsf $j =$
Some (*xor-abs* (*xor-from-bits* S (*xorsl* j)))
assumes *distinct* S
shows *check-xorL* F S *thresh xorsl* $i =$
appmc.check-xor F (*set* S) *thresh xorsf* i
unfolding *appmc.check-xor-def check-xorL-def*
using *size-xorL*[*OF assms*] **by** *presburger*

lemma *approxcore-xorsL*:
assumes $\bigwedge j.\ j <$ *length* $S - 1 \Longrightarrow$
xorsf $j =$

```
    Some (xor-abs (xor-from-bits S (xorsl j)))
  assumes S: distinct S
  shows approxcore-xorsL F S thresh xorsl =
    appmc.approxcore-xors F (set S) thresh xorsf
proof −
  have c:card (set S) = length S using S
  by (simp add: distinct-card)

  have ∗: find (check-xorL F S thresh xorsl) [1..<length S] =
   find (appmc.check-xor F (set S) thresh xorsf) [1..<card (set S)]
    unfolding c
    by (auto intro!: find-cong check-xorL[OF assms(1) S])

  have ∗∗: find (appmc.check-xor F
                  (set S) thresh xorsf)
            [Suc 0..<length S] =
           Some a ⟹
           j < a ⟹
           xorsf j =
           Some
            (xor-abs
              (xor-from-bits S
                (xorsl j))) for a j
    unfolding find-Some-iff
    by (auto simp add: assms(1))
  show ?thesis
  unfolding appmc.approxcore-xors-def approxcore-xorsL-def ∗ c
  apply (cases find (appmc.check-xor F (set S) thresh xorsf)
          [Suc 0..<length S])
  subgoal by clarsimp
  by (auto intro!: ApproxMCL.size-xorL simp add: ApproxMCL-axioms
assms ∗∗)
qed

definition approxmc-mapL::
  'fml ⇒ 'a list ⇒
  real ⇒ real ⇒ nat ⇒
  (nat ⇒ nat ⇒ (bool list × bool)) ⇒
  nat
  where approxmc-mapL F S ε δ n xorsLs = (
    let ε = appmc.mk-eps ε in
    let thresh = appmc.compute-thresh ε in
    if card (proj (set S) (sols F)) < thresh then
      card (proj (set S) (sols F))
    else
      let t = appmc.compute-t δ n in
      median t (approxcore-xorsL F S thresh ∘ xorsLs))

definition random-xorB :: nat ⇒ (bool list × bool) pmf
```

where *random-xorB n* =
pair-pmf
(*replicate-pmf n* (*bernoulli-pmf* (*1*/*2*)))
(*bernoulli-pmf* (*1*/*2*))

lemma *approxmc-mapL*:
assumes $\bigwedge i\ j.\ j < \mathit{length}\ S - 1 \Longrightarrow$
xorsFs i j =
Some (*xor-abs* (*xor-from-bits S* (*xorsLs i j*)))
assumes *S*: *distinct S*
shows
approxmc-mapL F S ε δ *n xorsLs* =
appmc.approxmc-map F (*set S*) ε δ *n xorsFs*
proof −
show *?thesis*
unfolding *approxmc-mapL-def appmc.approxmc-map-def Let-def*
using *assms* **by** (*auto intro*!: *median-cong approxcore-xorsL*)
qed

lemma *approxmc-mapL′*:
assumes *S*: *distinct S*
shows
approxmc-mapL F S ε δ *n xorsLs* =
appmc.approxmc-map F (*set S*) ε δ *n*
(*λi j. if j < length S − 1*
then Some (*xor-abs* (*xor-from-bits S* (*xorsLs i j*)))
else None)
apply (*intro approxmc-mapL*)
using *assms* **by** *auto*

lemma *bits-to-random-xor*:
assumes *distinct S*
shows *map-pmf*
(*λx. xor-abs* (*xor-from-bits S x*))
(*random-xorB* (*length S*)) =
random-xor (*set S*)
proof −
have *xor-abs* (*xor-from-bits S* (*a*,*b*)) = *apfst* (*set* ∘ *sublist-bits S*) (*a*,*b*) **for** *a b*
using *xor-abs-def* **by** (*auto simp add*: *xor-from-bits-def*)

then have ∗: (*λx. xor-abs* (*xor-from-bits S x*)) = *apfst* (*set* ∘ *sublist-bits S*)
by *auto*

have $\bigwedge x.\ x \in \mathit{set}\ S \Longrightarrow$
z x $\Longrightarrow$
$\exists\, b.\ (\exists\, n.\ S\ !\ n = x \wedge$

```
                map z S ! n = b ∧
                n < length S) ∧ b for z
    by (metis assms distinct-Ex1 nth-map)

  then have  set (map fst
              (filter snd
                (zip S (map z S)))) =
        {x ∈ set S. Some (z x) = Some True} for z
    by (auto elim: in-set-zipE simp add: in-set-zip image-def )

  then have ∗∗: map-pmf (set ∘ sublist-bits S)
      (replicate-pmf (length S) (bernoulli-pmf (1 / 2))) =
    map-pmf (λb. {x ∈ set S. b x = Some True})
      (Pi-pmf (set S) (Some undefined)
        (λ-. map-pmf Some (bernoulli-pmf (1 / 2))))
    apply (subst replicate-pmf-Pi-pmf[OF assms, where def = unde-
fined])
    apply (subst Pi-pmf-map[of -  - undefined])
   subgoal by (auto intro!: pmf.map-cong0 simp add: map-pmf-comp
sublist-bits-def)
    subgoal by (meson set-zip-leftD)
    unfolding map-pmf-comp sublist-bits-def o-def
    by (auto intro!: pmf.map-cong0)

  show ?thesis
    unfolding random-xorB-def
    apply (subst random-xor-from-bits)
    by (auto simp add: ∗ ∗∗ pair-map-pmf1[symmetric])
qed

lemma Pi-pmf-map-pmf-Some:
  assumes finite S
  shows Pi-pmf S None (λ-. map-pmf Some p) =
    map-pmf (λf v. if v ∈ S then Some (f v) else None)
    (Pi-pmf S def (λ-. p))
proof −
  have ∗: Pi-pmf S None (λ-. map-pmf Some p) =
    map-pmf (λf x. if x ∈ S then f x else None)
    (Pi-pmf S (Some def) (λ-. map-pmf Some p))
    apply (subst Pi-pmf-default-swap[OF assms])
     by auto

  show ?thesis unfolding ∗
    apply (subst Pi-pmf-map[OF assms, of  - def])
    subgoal by simp
    apply (simp add: map-pmf-comp o-def )
    by (metis comp-eq-dest-lhs)
qed
```

lemma *bits-to-random-xors*:
assumes *distinct S*
shows
map-pmf
(λ*f j*.
if j < *n*
then Some (*xor-abs* (*xor-from-bits S* (*f j*)))
else None)
(*Pi-pmf* {..<(*n*::*nat*)} *def* (λ-. *random-xorB* (*length S*))) =
random-xors (*set S*) *n*
unfolding *random-xors-def*
apply (*subst Pi-pmf-map-pmf-Some*)
subgoal using *assms* **by** *simp*
apply (*subst bits-to-random-xor*[*symmetric*, *OF assms*])
apply (*subst Pi-pmf-map*[**where** *dflt* = *def*, **where** *dflt'*=*xor-abs* (*xor-from-bits S def*)])
subgoal by *simp*
subgoal by *simp*
apply (*clarsimp simp add*: *map-pmf-comp o-def*)
by (*metis o-apply*)

lemma *bits-to-all-random-xors*:
assumes *distinct S*
assumes (λ*j*. *if j* < *n*
then Some (*xor-abs* (*xor-from-bits S* (*def1 j*)))
else None) = *def*
shows
map-pmf
((∘) (λ*f j*. *if j* < *n*
then Some (*xor-abs* (*xor-from-bits S* (*f j*)))
else None))
(*Pi-pmf* {*0*..<(*m*::*nat*)} *def1*
(λ-.
Pi-pmf {..<(*n*::*nat*)} *def2* (λ-. *random-xorB* (*length S*)))) =
Pi-pmf {*0*..<*m*} *def*
(λ*i*. *random-xors* (*set S*) *n*)
apply (*subst bits-to-random-xors*[*symmetric*, *OF assms*(*1*), *of - def2*])
apply (*subst Pi-pmf-map*[*OF* -])
using *assms*(*2*) **by** *auto*

definition *random-seed-xors*::*nat* ⇒ *nat* ⇒ (*nat* ⇒ *nat* ⇒ *bool list* × *bool*) *pmf*
where *random-seed-xors t l* =
(*prod-pmf* {*0*..<*t*}
(λ-. *prod-pmf* {..<*l*−*1*} (λ-. *random-xorB l*)))

lemma *approxmcL-sound*:
assumes δ: δ > *0* δ < *1*

```
  assumes ε: ε > 0
  assumes S: distinct S
  shows
    prob-space.prob
      (map-pmf (approxmc-mapL F S ε δ n)
        (random-seed-xors (appmc.compute-t δ n) (length S)))
      {c. real c ∈
        {real (card (proj (set S) (sols F))) / (1 + ε)..
          (1 + ε) * real (card (proj (set S) (sols F)))}}
      ≥ 1 − δ
proof −
  define def where def =
      (λj. if j < degree S
          then Some (xor-abs (xor-from-bits S (undefined j)))
          else None)
  have ∗: (map-pmf (approxmc-mapL F S ε δ n)
        (Pi-pmf {0..<appmc.compute-t δ n} undefined
          (λ-. Pi-pmf {..<length S − 1} undefined
            (λ-. random-xorB (length S))))) =
     (map-pmf (appmc.approxmc-map F (set S) ε δ n)
      (map-pmf ((∘) (λf.
          (λj. if j < length S − 1
                then Some (xor-abs (xor-from-bits S (f j)))
                else None)))
        (Pi-pmf {0..<appmc.compute-t δ n} undefined
          (λ-. Pi-pmf {..<length S − 1} undefined
                (λ-. random-xorB (length S))))))
    unfolding approxmc-mapL′[OF S]
    by (simp add: map-pmf-comp o-def)
  have ∗∗:
    (map-pmf (approxmc-mapL F S ε δ n)
        (Pi-pmf {0..<appmc.compute-t δ n} undefined
          (λ-. Pi-pmf {..<length S − 1} undefined
            (λ-. random-xorB (length S))))) =
    map-pmf (appmc.approxmc-map F (set S) ε δ n)
     (Pi-pmf {0..<appmc.compute-t δ n} def
       (λi. random-xors (set S) (card (set S) − 1)))
    unfolding ∗
    apply (subst bits-to-all-random-xors[OF S])
    using def-def
    by (auto simp add: assms(4) distinct-card)
  show ?thesis
    unfolding ∗∗ appmc.approxmc-map-eq random-seed-xors-def
    using δ(2) ε appmc.approxmc′-sound assms(1) by blast
qed


lemma approxmcL-sound′:
  assumes δ: δ > 0 δ < 1
```

```
  assumes ε: ε > 0
  assumes S: distinct S
  shows
    prob-space.prob
      (map-pmf (approxmc-mapL F S ε δ n)
        (random-seed-xors (appmc.compute-t δ n) (length S)))
      {c. real c ∉
        {real (card (proj (set S) (sols F))) / (1 + ε)..
          (1 + ε) * real (card (proj (set S) (sols F)))}} ≤ δ
proof −
  have prob-space.prob
      (map-pmf (approxmc-mapL F S ε δ n)
        (Pi-pmf {0..<appmc.compute-t δ n} undefined
          (λ-. Pi-pmf {..<length S − 1} undefined
            (λ-. random-xorB (length S)))))
      {c. real c ∉
        {real (card (proj (set S) (sols F))) / (1 + ε)..
          (1 + ε) * real (card (proj (set S) (sols F)))}} =
    1 − prob-space.prob
      (map-pmf (approxmc-mapL F S ε δ n)
        (Pi-pmf {0..<appmc.compute-t δ n} undefined
          (λ-. Pi-pmf {..<length S − 1} undefined
            (λ-. random-xorB (length S)))))
      {c. real c ∈
        {real (card (proj (set S) (sols F))) / (1 + ε)..
          (1 + ε) * real (card (proj (set S) (sols F)))}}
    apply (subst measure-pmf.prob-compl[symmetric])
    by (auto simp add: vimage-def)
  thus ?thesis using approxmcL-sound[OF assms, of F n] δ
    unfolding random-seed-xors-def
    by linarith
qed

end
```

7.2 ApproxMC certificate checker

```
definition str-of-bool :: bool ⇒ String.literal
  where str-of-bool b = (
  if b then STR ''true'' else STR ''false'')

fun str-of-nat-aux :: nat ⇒ char list ⇒ char list
  where str-of-nat-aux n acc = (
  let c = char-of-integer (of-nat (48 + n mod 10)) in
  if n < 10 then c # acc
  else str-of-nat-aux (n div 10) (c # acc))

definition str-of-nat :: nat ⇒ String.literal
  where str-of-nat n = String.implode (str-of-nat-aux n [])
```

type-synonym *'a sol = ('a × bool) list*

definition *canon-map-of* :: *('a × bool) list ⇒ ('a ⇒ bool)*
where *canon-map-of ls =*
(let m = map-of ls in
(λx. case m x of None ⇒ False | Some b ⇒ b))

lemma *canon-map-of*[*code*]:
shows *canon-map-of ls =*
(let m = Mapping.of-alist ls in
Mapping.lookup-default False m)
unfolding *canon-map-of-def lookup-default-def*
by (*auto simp add*: *lookup-of-alist*)

definition *proj-sol* :: *'a list ⇒ ('a ⇒ bool) ⇒ bool list*
where *proj-sol S w = map w S*

The following extended locale assumes additional support for syntactically working with solutions

locale *CertCheck = ApproxMCL sols enc-xor*
for *sols* :: *'fml ⇒ ('a ⇒ bool) set*
and *enc-xor* :: *'a list × bool ⇒ 'fml ⇒ 'fml +*
fixes *check-sol* :: *'fml ⇒ ('a ⇒ bool) ⇒ bool*
fixes *ban-sol* :: *'a sol ⇒ 'fml ⇒ 'fml*
assumes *sols-ban-sol*:
⋀F vs.
sols (ban-sol vs F) =
sols F ∩ {ω. map ω (map fst vs) ≠ map snd vs}
assumes *check-sol*:
⋀F w. check-sol F w ⟷ w ∈ sols F
begin

Assuming parameter access to an UNSAT checking oracle

context
fixes *check-unsat* :: *'fml ⇒ bool*
begin

Throughout this checker, INL indicates error, INR indicates success

definition *check-BSAT-sols*::
'fml ⇒ 'a list ⇒ nat ⇒ ('a ⇒ bool) list ⇒ String.literal + unit
where *check-BSAT-sols F S thresh cms = (*
let ps = map (proj-sol S) cms in
let b1 = list-all (check-sol F) cms in
let b2 = distinct ps in
let b3 =

```
    (length cms < thresh ⟶
      check-unsat (fold ban-sol (map (zip S) ps) F)) in
    if b1 ∧ b2 ∧ b3 then Inr ()
    else Inl (STR ''checks −−−'' +
      STR '' all valid sols: '' + str-of-bool b1 +
      STR '', all distinct sols: '' + str-of-bool b2 +
      STR '', unsat check (< thresh sols): '' + str-of-bool b3)
  )

definition BSAT ::
  'fml ⇒ 'a list ⇒ nat ⇒ ('a ⇒ bool) list ⇒ String.literal + nat
where BSAT F S thresh xs = (
  case check-BSAT-sols F S thresh xs of
    Inl err ⇒ Inl err
  | Inr - ⇒ Inr (length xs)
)


definition size-xorL-cert ::
  'fml ⇒ 'a list ⇒ nat ⇒
  (nat ⇒ (bool list × bool)) ⇒ nat ⇒
  (('a ⇒ bool) list) ⇒ String.literal + nat
  where size-xorL-cert F S thresh xorsl i xs = (
    let xors = map (xor-from-bits S ∘ xorsl) [0..<i]  in
    let Fenc = fold enc-xor xors F in
    BSAT Fenc S thresh xs
  )


fun approxcore-xorsL-cert ::
  'fml ⇒ 'a list ⇒ nat ⇒
  nat × ('a ⇒ bool) list × ('a ⇒ bool) list ⇒
  (nat ⇒ (bool list × bool))
  ⇒ String.literal + nat
where approxcore-xorsL-cert F S thresh (m,cert1,cert2) xorsl = (
  if 1 ≤ m ∧ m ≤ length S
  then
    case size-xorL-cert F S thresh xorsl (m−1) cert1 of
      Inl err ⇒ Inl (STR ''cert1 '' + err)
    | Inr n ⇒
    if n ≥ thresh
    then
      if m = length S
      then Inr (2 ^ length S)
      else
        case size-xorL-cert F S thresh xorsl m cert2 of
          Inl err ⇒ Inl (STR ''cert2 '' + err)
        | Inr c ⇒
          if c < thresh then Inr (2 ^ m ∗ c)
```

```
        else Inl (STR ''too many solutions at m added XORs'')
    else Inl (STR ''too few solutions at m−1 added XORs'')
  else
    Inl (STR ''invalid value of m, need 1 <= m <= |S|''))


definition find-t :: real ⇒ nat
where find-t δ = (
  case find (λi. appmc.raw-median-bound 0.14 i < δ) [0..<256] of
    Some m ⇒ m
  | None ⇒ appmc.fix-t δ
  )

fun fold-approxcore-xorsL-cert::
  'fml ⇒ 'a list ⇒ nat ⇒
  nat ⇒ nat ⇒
  (nat ⇒ (nat × ('a ⇒ bool) list × ('a ⇒ bool) list)) ⇒
  (nat ⇒ nat ⇒ (bool list × bool))
  ⇒ String.literal + (nat list)
  where
  fold-approxcore-xorsL-cert F S thresh t 0 cs xorsLs = Inr []
| fold-approxcore-xorsL-cert F S thresh t (Suc i) cs xorsLs = (
    let it = t − Suc i in
    case approxcore-xorsL-cert F S thresh (cs it) (xorsLs it) of
      Inl err ⇒ Inl (STR ''round '' + str-of-nat it + STR '' '' + err)
    | Inr n ⇒
      (case fold-approxcore-xorsL-cert F S thresh t i cs xorsLs of
          Inl err ⇒ Inl err
        | Inr ns ⇒ Inr (n # ns)))

definition calc-median::
  'fml ⇒ 'a list ⇒ nat ⇒ nat ⇒
  (nat ⇒ (nat × ('a ⇒ bool) list × ('a ⇒ bool) list)) ⇒
  (nat ⇒ nat ⇒ (bool list × bool)) ⇒
  String.literal + nat
  where calc-median F S thresh t ms xorsLs = (
      case fold-approxcore-xorsL-cert F S thresh t t ms xorsLs of
        Inl err ⇒ Inl err
      | Inr ls ⇒ Inr (sort ls ! (t div 2))
  )

fun certcheck::
  'fml ⇒ 'a list ⇒
  real ⇒ real ⇒
  (('a ⇒ bool) list ×
  (nat ⇒ (nat × ('a ⇒ bool) list × ('a ⇒ bool) list))) ⇒
  (nat ⇒ nat ⇒ (bool list × bool)) ⇒
  String.literal + nat
  where certcheck F S ε δ (m0,ms) xorsLs = (
```

```
    let ε = appmc.mk-eps ε in
    let thresh = appmc.compute-thresh ε in
    case BSAT F S thresh m0 of Inl err ⇒ Inl err
    | Inr Y ⇒
    if Y < thresh then Inr Y
    else
      let t = find-t δ in
      calc-median F S thresh t ms xorsLs)


context
  assumes check-unsat: ⋀F. check-unsat F ⟹ sols F = {}
begin

lemma sols-fold-ban-sol:
  showssols (fold ban-sol ls F) =
  sols F ∩ {ω. (∀ vs ∈ set ls. map ω (map fst vs) ≠ map snd vs)}
proof (induction ls arbitrary: F)
  case Nil
  then show ?case by auto
next
  case (Cons vs ls)
  show ?case
    using Cons(1) sols-ban-sol
    by auto
qed

lemma inter-cong-right:
  assumes ⋀x. x ∈ A ⟹ x ∈ B ⟷ x ∈ C
  shows A ∩ B = A ∩ C
  using assms by auto

lemma proj-sol-canon-map-of:
  assumes distinct S length S = length w
  shows proj-sol S (canon-map-of (zip S w)) = w
  using assms
  unfolding proj-sol-def canon-map-of-def
proof (induction w arbitrary: S)
  case Nil
  then show ?case
    by auto
next
  case (Cons a w)
  obtain s ss where ss: S = s # ss
    by (metis Cons.prems(2) Suc-le-length-iff order.refl)
  then show ?case
    apply clarsimp
   by (smt (z3) Cons.IH Cons.prems(2) add.right-neutral add-Suc-right
distinct.simps(2) list.size(4) local.Cons(2) map-eq-conv nat.inject)
```

qed

lemma *proj-sol-cong*:
assumes *restr* (*set S*) *A* = *restr* (*set S*) *B*
shows *proj-sol S A* = *proj-sol S B*
using *assms*
unfolding *proj-sol-def restr-def map-eq-conv*
by (*metis option.simps*(*1*))

lemma *canon-map-of-map-of*:
assumes *length S* = *length x*
assumes *canon-map-of* (*zip S x*) ∈ *A*
shows *map-of* (*zip S x*) ∈ *proj* (*set S*) *A*
proof −
define *f* **where** *f* = (λ*xa*. *case map-of* (*zip S x*) *xa of*
None ⇒ *False* | *Some b* ⇒ *b*)
have *map-of* (*zip S x*) =
(λ*y*. *if y* ∈ *set S then Some* (*f y*) *else None*)
unfolding *f-def fun-eq-iff*
using *map-of-zip-is-Some*[*OF assms*(*1*)]
by (*metis option.case-eq-if option.distinct*(*1*) *option.exhaust option.sel*)
thus *?thesis*
using *assms* **unfolding** *canon-map-of-def ApproxMCCore.proj-def restr-def image-def*
using *f-def* **by** *auto*
qed

lemma *proj-proj-sol-map-of-zip-1*:
assumes *distinct S length S* = *length w*
assumes *w*: *w* ∈ *rdb*
shows
map-of (*zip S w*) ∈
proj (*set S*) {ω. *proj-sol S* ω ∈ *rdb*}
apply (*intro canon-map-of-map-of*[*OF assms*(*2*)])
using *proj-sol-canon-map-of*[*OF assms*(*1*−*2*)] *w* **by** *auto*

lemma *proj-proj-sol-map-of-zip-2*:
assumes ⋀*bs*. *bs* ∈ *rdb* ⟹ *length bs* = *length S*
assumes *w*: *w* ∈ *proj* (*set S*) {ω. *proj-sol S* ω ∈ *rdb*}
shows
w ∈ (*map-of* ∘ *zip S*) ‘ *rdb*
proof −
obtain *ww* **where** *ww*: *proj-sol S ww* ∈ *rdb w* = *restr* (*set S*) *ww*
using *w* **unfolding** *ApproxMCCore.proj-def*
by *auto*

have *w* = *map-of* (*zip S* (*proj-sol S ww*))
unfolding *ww restr-def proj-sol-def map-of-zip-map*

```
    by auto

  thus ?thesis using ww
  by (auto simp add: image-def)
qed

lemma proj-proj-sol-map-of-zip:
  assumes distinct S
  assumes ⋀bs. bs ∈ rdb ⟹ length bs = length S
  shows
    proj (set S) {ω. proj-sol S ω ∈ rdb} =
    (map-of ∘ zip S) ‘ rdb
  apply (rule antisym)
  subgoal
    using proj-proj-sol-map-of-zip-2[OF assms(2)]
    by blast
  using assms(2)
  by (auto intro!: proj-proj-sol-map-of-zip-1[OF assms(1)])

definition ban-proj-sol ::'a list ⇒ ('a ⇒ bool) list ⇒ 'fml ⇒ 'fml
where ban-proj-sol S xs F =
    fold ban-sol (map (zip S ∘ proj-sol S) xs) F

lemma check-sol-imp-proj:
  assumes w ∈ sols F
  shows map-of (zip S (proj-sol S w)) ∈ proj (set S) (sols F)
  unfolding proj-sol-def map-of-zip-map ApproxMCCore.proj-def im-
age-def restr-def
  using assms by auto

lemma checked-BSAT-lower:
  assumes S: distinct S
  assumes check-BSAT-sols F S thresh xs = Inr ()
  shows length xs ≤ card (proj (set S) (sols F))
  length xs < thresh ⟹
    card (proj (set S) (sols F)) = length xs
proof −
  define Sxs where Sxs = map (proj-sol S) xs
  have dSxs: distinct Sxs
    using assms unfolding Sxs-def check-BSAT-sols-def Let-def
    by (auto split: if-splits)

  have lSxs: ⋀x. x ∈ set Sxs ⟹ length x = length S
    unfolding Sxs-def proj-sol-def by auto
  define SSxs where SSxs = map (zip S) Sxs
  have dSSxs: distinct (map map-of SSxs)
    unfolding SSxs-def
    using dSxs unfolding inj-on-def distinct-map
   by (smt (verit) assms(1) imageE lSxs list.set-map map-of-zip-inject)
```

have $*$: *set* (*map map-of SSxs*) $\subseteq$ *proj* (*set S*) (*sols F*)
unfolding *Sxs-def SSxs-def*
using *assms* **unfolding** *check-BSAT-sols-def Let-def*
by (*auto intro*!: *check-sol-imp-proj split*: *if-splits simp add*: *check-sol list-all-iff*)
have *length xs* = *card* (*set* (*map map-of SSxs*))
by (*metis SSxs-def Sxs-def dSSxs length-map length-remdups-card-conv remdups-id-iff-distinct*)

thus *length xs* $\leq$ *card* (*proj* (*set S*) (*sols F*))
by (*metis* $*$ *List.finite-set card-mono card-proj*(*1*))

have *frr1*: ($\forall$ *vs* $\in$ *set SSxs*. *map* ω (*map fst vs*) $\neq$ *map snd vs*) $\Longrightarrow$
($\forall$ *vs* $\in$ *set Sxs*. *proj-sol S* $\omega \neq$ *vs*) **for** ω
apply (*clarsimp simp add*: *proj-sol-def SSxs-def*)
by (*metis* (*mono-tags*, *lifting*) *in-set-zip nth-map*)
have *frr2*: ($\forall$ *vs* $\in$ *set Sxs*. *proj-sol S* $\omega \neq$ *vs*) $\Longrightarrow$
(*vs* $\in$ *set SSxs* $\Longrightarrow$ *map* ω (*map fst vs*) $\neq$ *map snd vs*) **for** *vs* ω
apply (*clarsimp simp add*: *proj-sol-def SSxs-def*)
by (*smt* (*z3*) *Sxs-def assms*(*1*) *length-map length-map length-map map-eq-conv map-fst-zip map-of-zip-inject mem-Collect-eq nth-map nth-map nth-map proj-sol-def set-conv-nth set-conv-nth zip-map-fst-snd*)

have *frr*: {ω. ($\forall$ *vs* $\in$ *set SSxs*. *map* ω (*map fst vs*) $\neq$ *map snd vs*)}
=
{ω. ($\forall$ *vs* $\in$ *set Sxs*. *proj-sol S* $\omega \neq$ *vs*)}
using *frr1 frr2* **by** *auto*

moreover {
assume *length xs* < *thresh*
then have *sols* (*ban-proj-sol S xs F*) = {}
apply (*intro check-unsat*)
using *assms*(*2*) **unfolding** *check-BSAT-sols-def Let-def*
by (*auto simp add*:*ban-proj-sol-def o-assoc split*: *if-splits*)

then have *sols F* $\cap$ {ω. ($\forall$ *vs* $\in$ *set Sxs*. *proj-sol S* $\omega \neq$ *vs*)} = {}
unfolding *ban-proj-sol-def sols-fold-ban-sol*
frr[*symmetric*]
by (*auto simp add*: *SSxs-def Sxs-def*)
then have *1*:*proj* (*set S*) (*sols F*) $\cap$
proj (*set S*)
{ω. $\forall$ *vs*$\in$*set Sxs*. *proj-sol S* $\omega \neq$ *vs*} = {}
unfolding *ApproxMCCore.proj-def*
using *proj-sol-cong*
by (*smt* (*verit*, *del-insts*) *disjoint-iff-not-equal image-iff mem-Collect-eq*)

have *2*: *proj* (*set S*) (*sols F*) $\cap$ $-$*proj* (*set S*) {ω. ($\forall$ *vs* $\in$ *set Sxs*. *proj-sol S* $\omega \neq$ *vs*)} =

```
      proj (set S) (sols F) ∩ proj (set S)  {ω. proj-sol S ω ∈ set Sxs}
      apply (intro inter-cong-right)
      by (auto intro!: proj-sol-cong simp add: ApproxMCCore.proj-def
)

    have 3: proj (set S)  {ω. proj-sol S ω ∈ set Sxs} = (map-of ∘ zip
S) ‘ (set Sxs)
      apply (intro proj-proj-sol-map-of-zip[OF S])
      using lSxs by auto

    have 4:  proj (set S) (sols F) ∩ (map-of ∘ zip S) ‘ (set Sxs) =
      (map-of ∘ zip S) ‘ (set Sxs)
      using ∗ SSxs-def by auto

    have ∗∗:proj (set S) (sols F) =
      proj (set S) (sols F) ∩ proj (set S) {ω. (∀ vs ∈ set Sxs. proj-sol
S ω ≠ vs)} ∪
      proj (set S) (sols F) ∩ −proj (set S) {ω. (∀ vs ∈ set Sxs. proj-sol
S ω ≠ vs)}
      by auto

    have card (proj (set S) (sols F)) =
      card ((map-of ∘ zip S) ‘ (set Sxs))
      apply (subst ∗∗)
      apply (subst card-Un-disjoint)
      using 1 2 3 4 by (auto simp add: card-proj(1))

    then have card (proj (set S) (sols F)) = length xs
      by (simp add: SSxs-def ‹length xs = card (set (map map-of
SSxs))›)
  }
  thus length xs < thresh ⟹ card (proj (set S) (sols F)) = length xs
  by auto
qed

lemma good-BSAT:
  assumes distinct S
  assumes BSAT F S thresh xs = Inr n
  shows n ≤ card (proj (set S) (sols F))
    n < thresh ⟹
      card (proj (set S) (sols F)) = n
  using checked-BSAT-lower[OF assms(1)] assms(2)
  by (auto simp add: BSAT-def split: if-splits sum.splits)

lemma size-xorL-cert:
  assumes distinct S
  assumes size-xorL-cert F S thresh xorsl i xs = Inr n
  shows
    size-xorL F S xorsl i ≥ n
```

```
    n < thresh ⟶ size-xorL F S xorsl i = n
  using assms unfolding size-xorL-def size-xorL-cert-def
  using good-BSAT by auto

lemma approxcore-xorsL-cert:
  assumes S: distinct S
  assumes approxcore-xorsL-cert F S thresh mc xorsl = Inr n
  shows approxcore-xorsL F S thresh xorsl = n
proof −
  obtain m cert1 cert2 where mc: mc = (m,cert1,cert2)
    using prod-cases3 by blast
  obtain nn1 where
    nn1:size-xorL-cert F S thresh xorsl (m−1) cert1 = Inr nn1
    using assms unfolding mc
    by (auto split: if-splits sum.splits)

  from  size-xorL-cert[OF S this]
  have nn1l:
    nn1 ≤ size-xorL F S xorsl (m − 1)
    nn1 < thresh ⟶ size-xorL F S xorsl (m − 1) = nn1 by auto

  have m: 1 ≤ m m ≤ length S
    nn1 ≥ thresh and
    ms: m = length S ∧ n = 2 ^ length S ∨
      m < length S
    using nn1 assms unfolding mc
    by (auto split: if-splits simp add: Let-def)

  have bnd: ⋀i. 1 ≤ i ⟹ i ≤ m −1 ⟹
      size-xorL F S xorsl i ≥ thresh
    using nn1l m(3)
    by (meson assms(1) dual-order.trans size-xorL-anti-mono)

  note ms
  moreover {
    assume ∗: m = length S
     then have find (check-xorL F S thresh xorsl) [1..<length S] =
None
      unfolding find-None-iff check-xorL-def
      by (auto simp add: bnd leD)
    then have ?thesis
      unfolding approxcore-xorsL-def
      using ∗ ms by force
  }
  moreover {
    assume ∗: m < length S

    obtain nn2 where
      nn2:size-xorL-cert F S thresh xorsl m cert2 = Inr nn2
```

```
      nn2 < thresh
      n = 2 ^ m * nn2
    using assms * unfolding mc
    by (auto split: if-splits sum.splits)

  from size-xorL-cert[OF S nn2(1)]
  have nn2l:
    size-xorL F S xorsl m = nn2
    using nn2(2) by blast

  then have find (check-xorL F S thresh xorsl) [Suc 0..<length S]
= Some m
    apply (intro find-upto-SomeI)
    subgoal by (auto  simp add: m * bnd check-xorL-def leD)
    subgoal
      using * calculation(1) size-xorL-cert(2) nn2
      by (auto  simp add: m * bnd check-xorL-def leD)
    subgoal using m(1) by linarith
    by (auto  simp add: m * bnd check-xorL-def leD)

  then have ?thesis
    unfolding approxcore-xorsL-def using nn2 nn2l
    by auto
 }
 ultimately show ?thesis by auto
qed

lemma fold-approxcore-xorsL-cert:
 assumes S: distinct S
 assumes i ≤ t
 assumes fold-approxcore-xorsL-cert F S thresh t i cs xorsLs = Inr
ns
 shows map (approxcore-xorsL F S thresh ∘ xorsLs) [t−i..<t] = ns
 using assms(2−3)
proof (induction i arbitrary: ns)
 case 0
 then show ?case
   by auto
next
 case c:(Suc i)
 from c(3)
 obtain n nss where *:ns = n # nss
    fold-approxcore-xorsL-cert F S thresh t i cs xorsLs = Inr nss
     approxcore-xorsL-cert F S thresh (cs (t−Suc i)) (xorsLs (t−Suc
i)) = Inr n
   by (auto simp add: Let-def split: sum.splits)

 have i ≤ t using c by auto
 from c(1)[OF this *(2)]
```

```
  have 2: nss =
    map (approxcore-xorsL F S thresh ∘ xorsLs) [t − i..<t]
    by auto

  have i:[t − Suc i..<t] = (t − Suc i) # [t − i..<t]
    apply (subst upt-rec)
    using c(2)
    using Suc-diff-Suc Suc-le-lessD by presburger

  show ?case
    unfolding i ∗
    apply (clarsimp simp add: 2 )
    using  2 ∗(3) approxcore-xorsL-cert assms(1) by blast
qed

lemma calc-median:
  assumes S: distinct S
  assumes calc-median F S thresh t ms xorsLs = Inr n
  shows median t (approxcore-xorsL F S thresh ∘ xorsLs) = n
  using assms
  unfolding calc-median-def  median-def
  apply (clarsimp simp add: assms split: if-splits sum.splits)
  using  fold-approxcore-xorsL-cert[OF S]
  by (metis diff-is-0-eq′ dual-order.refl)

lemma compute-t-find-t[simp]:
  shows appmc.compute-t δ (find-t δ) = find-t δ
  unfolding find-t-def appmc.compute-t-def
  apply (clarsimp simp add: option.case-eq-if)
  unfolding find-Some-iff
  by auto

lemma certcheck:
  assumes distinct S
  assumes certcheck F S ε δ (m0,ms) xorsLs = Inr n
  shows approxmc-mapL F S ε δ (find-t δ) xorsLs = n
  using assms(2)
  unfolding approxmc-mapL-def
   using good-BSAT apply (clarsimp split: sum.splits if-splits simp
add: Let-def)
  subgoal using order-le-less-trans assms by blast
  using assms order.strict-trans1
  by (meson assms(1) calc-median)

lemma certcheck′:
  assumes distinct S
  assumes ¬isl (certcheck F S ε δ m xorsLs)
  shows projr (certcheck F S ε δ m xorsLs) =
    approxmc-mapL F S ε δ (find-t δ) xorsLs
```

by (*metis certcheck assms*(*1*) *assms*(*2*) *sum.collapse*(*2*) *surj-pair*)

lemma *certcheck-sound*:
assumes δ: $\delta > 0$ $\delta < 1$
assumes ε: $\varepsilon > 0$
assumes S: *distinct S*
shows
measure-pmf.prob
(*map-pmf* (λr. *certcheck F S* ε δ (*f r*) *r*)
(*random-seed-xors* (*find-t* δ) (*length S*)))
{*c*. ¬*isl c* ∧
real (*projr c*) ∉
{*real* (*card* (*proj* (*set S*) (*sols F*))) / (*1* + ε)..
(*1* + ε) ∗ *real* (*card* (*proj* (*set S*) (*sols F*)))}} ≤ δ
proof −
have *measure-pmf.prob*
(*map-pmf* (λr. *certcheck F S* ε δ (*f r*) *r*)
(*random-seed-xors* (*find-t* δ) (*length S*)))
{*c*. ¬*isl c* ∧
real (*projr c*) ∉
{*real* (*card* (*proj* (*set S*) (*sols F*))) / (*1* + ε)..
(*1* + ε) ∗ *real* (*card* (*proj* (*set S*) (*sols F*)))}} ≤
prob-space.prob
(*map-pmf* (*approxmc-mapL F S* ε δ (*find-t* δ))
(*random-seed-xors* (*appmc.compute-t* δ (*find-t* δ)) (*length S*)))
{*c*. *real c* ∉
{*real* (*card* (*proj* (*set S*) (*sols F*))) / (*1* + ε)..
(*1* + ε) ∗ *real* (*card* (*proj* (*set S*) (*sols F*)))}}
unfolding *measure-map-pmf compute-t-find-t*
by (*auto intro*!: *measure-pmf.finite-measure-mono simp add*: *certcheck'*[*OF S*])
also have ... ≤ δ
by (*intro approxmcL-sound'*[*OF assms*])
finally show *?thesis* **by** *auto*
qed

lemma *certcheck-promise-complete*:
assumes δ: $\delta > 0$ $\delta < 1$
assumes ε: $\varepsilon > 0$
assumes S: *distinct S*
assumes r: $\bigwedge r$.
$r \in$ *set-pmf* (*random-seed-xors* (*find-t* δ) (*length S*)) ⟹
¬*isl* (*certcheck F S* ε δ (*f r*) *r*)
shows
measure-pmf.prob
(*map-pmf* (λr. *certcheck F S* ε δ (*f r*) *r*)
(*random-seed-xors* (*find-t* δ) (*length S*)))

```
    {c. real (projr c) ∈
      {real (card (proj (set S) (sols F))) / (1 + ε)..
        (1 + ε) * real (card (proj (set S) (sols F)))}} ≥ 1 - δ
proof -
  have
   measure-pmf.prob
     (map-pmf (λr. certcheck F S ε δ (f r) r)
       (random-seed-xors (find-t δ) (length S)))
     {c. real (projr c) ∈
       {real (card (proj (set S) (sols F))) / (1 + ε)..
         (1 + ε) * real (card (proj (set S) (sols F)))}} =
   measure-pmf.prob
     (map-pmf (approxmc-mapL F S ε δ (find-t δ))
       (random-seed-xors (appmc.compute-t δ (find-t δ)) (length S)))
     {c. real c ∈
       {real (card (proj (set S) (sols F))) / (1 + ε)..
         (1 + ε) * real (card (proj (set S) (sols F)))}}
    unfolding measure-map-pmf compute-t-find-t
   by (auto intro!: measure-pmf.measure-pmf-eq simp add: certcheck'[OF
S] r)
  also have ... ≥ 1 -  δ
    by (intro approxmcL-sound[OF assms(1-4)])
  finally show ?thesis by auto
qed

end

lemma certcheck-code[code]:
   certcheck F S ε δ (m0,ms) xorsLs = (
    if δ > 0 ∧ δ < 1 ∧ ε > 0 ∧ distinct S then
      (let ε = appmc.mk-eps ε in
      let thresh = appmc.compute-thresh ε in
      case BSAT F S thresh m0 of Inl err ⇒ Inl err
      | Inr Y ⇒
      if Y < thresh then Inr Y
      else
        let t = find-t δ in
        calc-median F S thresh t ms xorsLs)
     else Code.abort (STR ''invalid inputs'')
       (λ-. certcheck F S ε δ (m0,ms) xorsLs))
  by auto

end

end

end
```

8 ApproxMC certification for CNF-XOR

This concretely instantiates the locales with a syntax and semantics for CNF-XOR, giving us a certificate checker for approximate counting in this theory.

theory *CertCheck-CNF-XOR* **imports**
ApproxMCAnalysis
CertCheck
HOL.String HOL−Library.Code-Target-Numeral
Show.Show-Real
begin

This follows CryptoMiniSAT's CNF-XOR formula syntax. A clause is a list of literals (one of which must be satisfied). An XOR constraint has the form $l_1 + l_2 + \ldots + l_n = 1$ where addition is taken over F_2. Syntactically, they are specified by the list of LHS literals. Variables are natural numbers (in practice, variable 0 is never used)

datatype *lit* = *Pos nat* | *Neg nat*
type-synonym *clause* = *lit list*
type-synonym *cmsxor* = *lit list*
type-synonym *fml* = *clause list* × *cmsxor list*

type-synonym *assignment* = *nat* ⇒ *bool*

definition *sat-lit* :: *assignment* ⇒ *lit* ⇒ *bool* **where**
sat-lit w l = (*case l of Pos x* ⇒ *w x* | *Neg x* ⇒ ¬*w x*)

definition *sat-clause* :: *assignment* ⇒ *clause* ⇒ *bool* **where**
sat-clause w C = (∃ *l* ∈ *set C*. *sat-lit w l*)

definition *sat-cmsxor* :: *assignment* ⇒ *cmsxor* ⇒ *bool* **where**
sat-cmsxor w C = *odd* ((*sum-list* (*map* (*of-bool* ∘ (*sat-lit w*)) *C*))::*nat*)

definition *sat-fml* :: *assignment* ⇒ *fml* ⇒ *bool*
where
sat-fml w f = (
(∀ *C* ∈ *set* (*fst f*). *sat-clause w C*) ∧
(∀ *C* ∈ *set* (*snd f*). *sat-cmsxor w C*))

definition *sols* :: *fml* ⇒ *assignment set*
where *sols f* = {*w*. *sat-fml w f*}

lemma *sat-fml-cons*[*simp*]:
shows
sat-fml w (*FC*, *x* # *FX*) ⟷
sat-fml w (*FC*,*FX*) ∧ *sat-cmsxor w x*

sat-fml w (c # FC, FX) ⟷
sat-fml w (FC,FX) ∧ sat-clause w c
unfolding *sat-fml-def* **by** *auto*

fun *enc-xor* :: *nat xor ⇒ fml ⇒ fml*
where
enc-xor (x,b) (FC,FX) = (
if b then (FC, map Pos x # FX)
else
case x of
[] ⇒ (FC,FX)
| (v#vs) ⇒ (FC, (Neg v # map Pos vs) # FX))

lemma *sols-enc-xor*:
shows *sols (enc-xor (x,b) (FC,FX)) =*
sols (FC,FX) ∩ {ω. satisfies-xorL (x,b) ω}
unfolding *sols-def*
by (*cases x*; *auto simp add*: *satisfies-xorL-def sat-cmsxor-def o-def sat-lit-def list.case-eq-if*)

definition *check-sol* :: *fml ⇒ (nat ⇒ bool) ⇒ bool*
where *check-sol fml w = (*
list-all (list-ex (sat-lit w)) (fst fml) ∧
list-all (sat-cmsxor w) (snd fml))

definition *ban-sol* :: *(nat × bool) list ⇒ fml ⇒ fml*
where *ban-sol vs fml =*
((map (λ(v,b). if b then Neg v else Pos v) vs)#fst fml, snd fml)

lemma *check-sol-sol*:
shows *w ∈ sols F ⟷*
check-sol F w
unfolding *check-sol-def sols-def sat-fml-def*
apply *clarsimp*
by (*metis Ball-set-list-all Bex-set-list-ex sat-clause-def*)

lemma *ban-sat-clause*:
shows *sat-clause w (map (λ(v, b). if b then Neg v else Pos v) vs)*
⟷
map w (map fst vs) ≠ map snd vs
unfolding *sat-clause-def*
by (*force simp add*: *sat-lit-def split*: *if-splits*)

lemma *sols-ban-sol*:
shows*sols (ban-sol vs F) =*
sols F ∩
{ω. map ω (map fst vs) ≠ map snd vs}

unfolding *ban-sol-def sols-def*
by (*auto simp add*: *ban-sat-clause*)

global-interpretation *CertCheck-CNF-XOR* :
CertCheck sols enc-xor check-sol ban-sol
defines
random-seed-xors = *CertCheck-CNF-XOR.random-seed-xors* **and**
fix-t = *CertCheck-CNF-XOR.appmc.fix-t* **and**
find-t = *CertCheck-CNF-XOR.find-t* **and**
BSAT = *CertCheck-CNF-XOR.BSAT* **and**
check-BSAT-sols = *CertCheck-CNF-XOR.check-BSAT-sols* **and**
size-xorL-cert = *CertCheck-CNF-XOR.size-xorL-cert* **and**
approxcore-xorsL = *CertCheck-CNF-XOR.approxcore-xorsL* **and**
fold-approxcore-xorsL-cert = *CertCheck-CNF-XOR.fold-approxcore-xorsL-cert*
and
approxcore-xorsL-cert = *CertCheck-CNF-XOR.approxcore-xorsL-cert*
and
calc-median = *CertCheck-CNF-XOR.calc-median* **and**
certcheck = *CertCheck-CNF-XOR.certcheck*
apply *unfold-locales*
subgoal by (*metis sols-enc-xor surj-pair*)
subgoal by (*metis sols-ban-sol*)
by (*metis check-sol-sol*)

8.1 Blasting XOR constraints to CNF

This formalizes the usual linear conversion from CNF-XOR into CNF. It is not necessary to use this conversion for solvers that support CNF-XOR formulas natively.

definition *negate-lit* :: *lit* ⇒ *lit*
where *negate-lit l* = (*case l of Pos x* ⇒ *Neg x* | *Neg x* ⇒ *Pos x*)

fun *xor-clauses* :: *cmsxor* ⇒ *bool* ⇒ *clause list*
where
xor-clauses [] *b* = (*if b then* [[]] *else* [])
| *xor-clauses* (*x*#*xs*) *b* =
(*let p-x* = *xor-clauses xs b in*
let n-x = *xor-clauses xs* (¬*b*) *in*
map (λ*c*. *x* # *c*) *p-x* @ *map* (λ*c*. *negate-lit x* # *c*) *n-x*)

lemma *sat-cmsxor-nil*[*simp*]:
shows¬ (*sat-cmsxor w* [])
unfolding *sat-cmsxor-def*
by *auto*

lemma *sat-cmsxor-cons*:
shows *sat-cmsxor w* (*x* # *xs*) =

```
    (if sat-lit w x then ¬ (sat-cmsxor w xs) else sat-cmsxor w xs)
  unfolding sat-cmsxor-def
  by auto

lemma sat-cmsxor-append:
  shows sat-cmsxor w (xs @ ys) =
    (if sat-cmsxor w xs then ¬ (sat-cmsxor w ys) else sat-cmsxor w ys)
proof (induction xs)
  case Nil
  then show ?case
    by (auto simp add: sat-cmsxor-def)
next
  case (Cons x xs)
  then show ?case
    by (auto simp add: sat-cmsxor-cons)
qed

definition sat-clauses:: assignment ⇒ clause list ⇒ bool
  where sat-clauses w cs = (∀ c ∈ set cs. sat-clause w c)

lemma sat-clauses-append:
  shows sat-clauses w (xs @ ys) =
    (sat-clauses w xs ∧ sat-clauses w ys)
  unfolding sat-clauses-def by auto

lemma sat-clauses-map:
  shows sat-clauses w (map ((#) x) cs) =
    (sat-lit w x ∨ sat-clauses w cs)
  unfolding sat-clauses-def sat-clause-def by auto

lemma sat-lit-negate-lit[simp]:
  sat-lit w (negate-lit l) = (¬sat-lit w l)
  apply (cases l)
  by (auto simp add: negate-lit-def sat-lit-def)

lemma sols-xor-clauses:
  shows
    sat-clauses w (xor-clauses xs b) ⟷
    (sat-cmsxor w xs = b)
proof (induction xs arbitrary: b)
  case Nil
  then show ?case
    by (auto simp add: sat-cmsxor-def sat-clauses-def sat-clause-def)
next
  case (Cons x xs b)
  have *: (sat-cmsxor w (x # xs) = b) =
    (if sat-lit w x
     then (sat-cmsxor w xs = (¬b))
     else (sat-cmsxor w xs = b)) unfolding sat-cmsxor-cons
```

```
    by auto

  have sat-clauses w (xor-clauses (x # xs) b) ⟷
    ((sat-lit w x ∨ sat-clauses w (xor-clauses xs b)) ∧
     (¬(sat-lit w x) ∨ sat-clauses w (xor-clauses xs (¬ b))))
   unfolding xor-clauses.simps Let-def sat-clauses-append sat-clauses-map
    by auto
  moreover have ... = (
     (sat-lit w x ∨ (sat-cmsxor w xs = b)) ∧
     (¬(sat-lit w x) ∨ (sat-cmsxor w xs = (¬ b))))
    using Cons.IH by auto
  moreover have ... = (sat-cmsxor w (x # xs) = b)
    unfolding ∗ by auto
  ultimately show ?case
    by auto
qed


definition var-lit :: lit ⇒ nat
  where var-lit l = (case l of Pos x ⇒ x  | Neg x ⇒ x)

definition var-lits :: lit list ⇒ nat
  where var-lits ls = fold max (map var-lit ls) 0

lemma sat-lit-same:
  assumes ⋀x. x ≤ var-lit l ⟹ w x = w′ x
  shows sat-lit w l = sat-lit w′ l
  using assms
  apply (cases l)
  by (auto simp add: sat-lit-def var-lit-def)

lemma var-lits-eq:
  var-lits ls = Max (set (0 # map var-lit ls))
  unfolding var-lits-def Max.set-eq-fold
  by auto

lemma sat-lits-same:
  assumes ⋀x. x ≤ var-lits c ⟹ w x = w′ x
  shows sat-clause w c = sat-clause w′ c
  using assms
  unfolding sat-clause-def var-lits-eq sat-lit-same
 by (smt (verit) List.finite-set Max-ge dual-order.trans image-subset-iff
list.set-map sat-lit-same set-subset-Cons)

lemma le-var-lits-in:
  assumes y ∈ set ys v ≤ var-lit y
  shows v ≤ var-lits ys
  using assms unfolding var-lits-eq
   by (metis List.finite-set Max-ge dual-order.trans imageI insertCI
```

list.set(2) list.set-map)

lemma *sat-cmsxor-same*:
assumes $\bigwedge x.\ x \leq$ *var-lits xs* $\Longrightarrow$ *w x* = *w′ x*
shows *sat-cmsxor w xs* = *sat-cmsxor w′ xs*
using *assms*
proof (*induction xs*)
case *Nil*
then show *?case*
unfolding *sat-cmsxor-def*
by *auto*
next
case *ih*:(*Cons x xs*)
have *1*: *sat-lit w x* = *sat-lit w′ x*
apply (*intro sat-lit-same*)
using *ih*(*2*)
by (*metis le-var-lits-in list.set-intros*(*1*))
have *2*: *sat-cmsxor w xs* = *sat-cmsxor w′ xs*
apply (*intro ih*(*1*))
using *ih*(*2*)
by (*smt* (*verit*) *List.finite-set Max-ge-iff empty-not-insert insert-iff list.set*(*2*) *list.simps*(*9*) *var-lits-eq*)
show *?case*
unfolding *sat-cmsxor-cons*
using *1 2* **by** *presburger*
qed

lemma *sat-cmsxor-split*:
assumes *u*: *var-lits xs* < *u var-lits ys* < *u*
assumes *w′*: *w′* = (λ*x*. *if x* = *u then* ¬ *sat-cmsxor w xs else w x*)
shows
(*sat-cmsxor w* (*xs* @ *ys*) =
(*sat-cmsxor w′* (*Pos u* # *xs*) ∧
sat-cmsxor w′ (*Neg u* # *ys*)))
proof −
have *xs*: *sat-cmsxor w′ xs* = *sat-cmsxor w xs*
apply (*intro sat-cmsxor-same*)
using *u* **unfolding** *w′* **by** *auto*
have *ys*: *sat-cmsxor w′ ys* = *sat-cmsxor w ys*
apply (*intro sat-cmsxor-same*)
using *u* **unfolding** *w′* **by** *auto*

show *?thesis*
unfolding *sat-cmsxor-append sat-cmsxor-cons xs ys*
unfolding *w′* **by** (*auto simp add*: *sat-lit-def*)
qed

fun *split-xor* ::*nat* ⇒ *cmsxor* ⇒ *cmsxor list* × *nat* ⇒ *cmsxor list* × *nat*
  where *split-xor k xs* (*acc*,*u*) = (
    if length xs ≤ *k* + *3 then* (*xs* # *acc*, *u*)
    else (
      let xs1 = *take* (*k* + *2*) *xs in*
      let xs2 = *drop* (*k* + *2*) *xs in*
      split-xor k (*Neg u* # *xs2*) ((*Pos u* # *xs1*) # *acc*, *u*+*1*)
)
)

declare *split-xor.simps*[*simp del*]

lemma *split-xor-bound*:
  assumes *split-xor k xs* (*acc*,*u*) = (*acc*′,*u*′)
  shows *u* ≤ *u*′
  using *assms*
proof (*induction length xs arbitrary*: *xs acc u acc*′ *u*′ *rule*: *less-induct*)
  case *less*
  have *length xs* ≤ *k* + *3* ∨ ¬ (*length xs* ≤ *k* + *3*) **by** *auto*
  moreover {
    assume *length xs* ≤ *k* + *3*
    then have *u* ≤ *u*′
      using *less*(*2*) *split-xor.simps* **by** *auto*
  }
  moreover {
    assume *s*: ¬ (*length xs* ≤ *k* + *3*)
    then have *l*: *length* (*Neg u* # *drop* (*Suc* (*Suc k*)) *xs*) < *length xs*
      by *auto*
    have *Suc u* ≤ *u*′
      using *s less*(*2*)
      unfolding *split-xor.simps*[*of k xs*]
      using *less*(*1*)[*OF l*] **by** *auto*
    then have *u* ≤ *u*′ **by** *auto*
  }
  ultimately show *?case* **by** *auto*
qed

lemma *var-lits-append*:
  shows *var-lits xs* ≤ *var-lits* (*xs* @ *ys*)
    var-lits ys ≤ *var-lits* (*xs* @ *ys*)
  unfolding *var-lits-eq*
  by *auto*

lemma *fold-max-eq*:
  assumes *i* ≤ *u*
  shows *fold max ls u* = *max u* (*fold max ls* (*i*::*nat*))
  using *assms*
  apply (*induction ls arbitrary*: *i*)

subgoal by *clarsimp*
apply *clarsimp*
by (*smt* (*verit*) *List.finite-set Max.set-eq-fold Max-ge-iff empty-iff insert-iff list.set*(2) *max.orderI max-def pre-arith-simps*(3))

lemma *split-xor-sound*:
assumes *sat-cmsxor w xs* $\bigwedge x.\ x \in set\ acc \Longrightarrow$ *sat-cmsxor w x*
assumes *u*: *var-lits xs* $< u$ $\bigwedge x.\ x \in set\ acc \Longrightarrow$ *var-lits x* $< u$
assumes *split-xor k xs* (*acc*,*u*) = (*acc*′,*u*′)
obtains *w*′ **where**
$\bigwedge x.\ x < u \Longrightarrow w\ x = w'\ x$
$\bigwedge x.\ x \in set\ acc' \Longrightarrow$ *sat-cmsxor w*′ *x*
$\bigwedge x.\ x \in set\ acc' \Longrightarrow$ *var-lits x* $< u'$
using *assms*
proof (*induction length xs arbitrary*: *w xs acc u acc*′ *u*′ *thesis rule*: *less-induct*)
case *less*
have *length xs* $\leq k + 3 \vee \neg$ (*length xs* $\leq k + 3$) **by** *auto*
moreover {
assume *length xs* $\leq k + 3$
then have ∗: *acc*′ = *xs* # *acc*
using *less*(7) *split-xor.simps*
by *auto*
then have
$\bigwedge x.\ x < u \Longrightarrow w\ x = w\ x$
$\bigwedge x.\ x \in set\ acc' \Longrightarrow$ *sat-cmsxor w x*
$\bigwedge x.\ x \in set\ acc' \Longrightarrow$ *var-lits x* $< u'$
subgoal by *meson*
subgoal using *less*
by (*metis* ∗ *set-ConsD*)
using *less*
by (*metis* ∗ *order-trans-rules*(22) *set-ConsD split-xor-bound*)
}
moreover {
assume *s*: ¬ (*length xs* $\leq k + 3$)
define *xs1* **where** *xs1*:*xs1* = *take* ($k + 2$) *xs*
define *xs2* **where** *xs2*:*xs2* = *drop* ($k + 2$) *xs*
have *sp*: *split-xor k* (*Neg u* # *xs2*) ((*Pos u* # *xs1*) # *acc*, *u*+1) = (*acc*′,*u*′)
by (*metis less*(7) *s split-xor.simps xs1 xs2*)
have *l*: *length* (*Neg u* # *xs2*) < *length xs*
using *s xs2* **by** *auto*

have *xs*: *xs* = *xs1* @ *xs2* **by** (*simp add*: *xs1 xs2*)

define *w*′ **where** *w*′: *w*′ =
(λ*x*. *if x* = *u then* ¬ *sat-cmsxor w xs1 else w x*)

have *vl*: *var-lits xs1* < *u var-lits xs2* < *u*
apply (*metis less*(*5*) *order-trans-rules*(*21*) *var-lits-append*(*1*) *xs*)
by (*metis less*(*5*) *order-trans-rules*(*21*) *var-lits-append*(*2*) *xs*)

from *sat-cmsxor-split*[*OF this w'*]
have *satws1*: *sat-cmsxor w'* (*Pos u # xs1*)
and *satws2*: *sat-cmsxor w'* (*Neg u # xs2*)
using *less*(*3*) *xs* **by** *auto*

have *satacc*: ⋀*x*. *x* ∈ *set* ((*Pos u # xs1*) # *acc*) ⟹
sat-cmsxor w' x
by (*metis less*(*4*) *less*(*6*) *not-less sat-cmsxor-same satws1 set-ConsD w'*)

have *v1*: *var-lits* (*Neg u # xs2*) < *u* + *1*
unfolding *var-lits-def*
apply (*simp add*: *var-lit-def*)
using *vl var-lits-def fold-max-eq*
by (*metis le-add2 le-add-same-cancel2 less-Suc-eq max.absorb3*)

have *fold max* (*map var-lit xs1*) *u* < *Suc u*
using *vl var-lits-def*
by (*smt* (*verit*, *best*) *List.finite-set Max.set-eq-fold Max-ge-iff dual-order.trans empty-iff insert-iff lessI less-or-eq-imp-le list.set*(*2*) *not-less*)
moreover have ⋀*x*. *x* ∈ *set acc* ⟹
fold max (*map var-lit x*) *0* < *Suc u*
by (*metis less*(*6*) *less-SucI var-lits-def*)
ultimately have *v2*:⋀*x*. *x* ∈ *set* ((*Pos u # xs1*) # *acc*) ⟹ *var-lits x* < *u* + *1*
unfolding *var-lits-def*
by (*auto simp add*: *var-lit-def*)

obtain *w''* **where**
w'': ⋀*x*. *x* < *u* + *1* ⟹ *w' x* = *w'' x*
⋀*x*. *x* ∈ *set acc'* ⟹ *sat-cmsxor w'' x*
⋀*x*. *x* ∈ *set acc'* ⟹ *var-lits x* < *u'*
using *less*(*1*)[*OF l - satws2 satacc v1 v2 sp*]
by *auto*

have ⋀*x*. *x* < *u* ⟹ *w x* = *w'' x*
using *w''*(*1*)
unfolding *w'*
using *less-Suc-eq* **by** *fastforce*

then have ∃ *w''*. (
(∀ *x*. *x* < *u* ⟶ *w x* = *w'' x*) ∧
(∀ *x*. *x* ∈ *set acc'* ⟶ *sat-cmsxor w'' x*) ∧
(∀ *x*. *x* ∈ *set acc'* ⟶ *var-lits x* < *u'*))

```
    using w''(2-3) by auto
  }
  ultimately show ?case
    using less(2)
    by (metis (mono-tags, lifting))
qed

definition split-xors ::nat ⇒ nat ⇒ cmsxor list ⇒ cmsxor list
where split-xors k u xs = fst (fold (split-xor k) xs ([],u))

lemma split-xors-sound:
  assumes ⋀x. x ∈ set xs ⟹ sat-cmsxor w x
          ⋀x. x ∈ set acc ⟹ sat-cmsxor w x
  assumes u: ⋀x. x ∈ set xs ⟹ var-lits x < u
      ⋀x. x ∈ set acc ⟹ var-lits x < u
  assumes fold (split-xor k) xs (acc,u) = (acc',u')
  obtains w' where
    ⋀x. x < u ⟹ w x = w' x
    ⋀x. x ∈ set acc' ⟹ sat-cmsxor w' x
    ⋀x. x ∈ set acc' ⟹ var-lits x < u'
  using assms
proof (induction xs arbitrary: w acc u acc' u')
  case Nil
  then show ?case
    by auto
next
  case ih:(Cons x xs)
  obtain acc'' u'' where x: split-xor k x (acc, u) = (acc'',u'')
    by fastforce
  from split-xor-sound[OF - - - - this]
  obtain w'' where
    w'': ⋀x. x < u ⟹ w x = w'' x
    ⋀x. x ∈ set acc'' ⟹ sat-cmsxor w'' x
    ⋀x. x ∈ set acc'' ⟹ var-lits x < u''
   by (smt (verit, del-insts) ih(4) ih(5) ih(6) ih.prems(2) list.set-intros(1))
  have rw: fold (split-xor k) xs (acc'',u'') = (acc', u')
    using ih(7) x by auto
  have 1: ⋀x. x ∈ set xs ⟹sat-cmsxor w'' x
   by (metis basic-trans-rules(22) ih(3) ih(5) list.set-intros(2) not-less
sat-cmsxor-same w''(1))
  have 2: ⋀x. x ∈ set xs ⟹ var-lits x < u''
   by (meson ih(5) list.set-intros(2) order-trans-rules(22) split-xor-bound
x)
  show ?case
    using ih(1)[OF - 1 w''(2) 2 w''(3) rw]
     by (smt (verit, best) basic-trans-rules(22) ih(2) split-xor-bound
w''(1) x)
qed
```

definition *var-fml* :: *fml* ⇒ *nat*
where *var-fml f* =
max (*fold max* (*map var-lits* (*fst f*)) *0*)
(*fold max* (*map var-lits* (*snd f*)) *0*)

lemma *var-fml-eq*:
var-fml f =
max (*Max* (*set* (*0* # *map var-lits* (*fst f*))))
(*Max* (*set* (*0* # *map var-lits* (*snd f*))))
unfolding *var-fml-def Max.set-eq-fold*
by *auto*

definition *split-fml* :: *nat* ⇒ *fml* ⇒ *fml*
where *split-fml k f* = (
let u = *var-fml f* + *1 in*
(*fst f*, (*split-xors k u* (*snd f*)))
)

lemma *var-lits-var-fml*:
shows ⋀*x*. *x* ∈ *set* (*snd F*) ⟹ *var-lits x* ≤ *var-fml F*
⋀*x*. *x* ∈ *set* (*fst F*) ⟹ *var-lits x* ≤ *var-fml F*
unfolding *var-fml-eq*
subgoal
apply *clarsimp*
by (*meson List.finite-set Max-ge finite-imageI finite-insert image-subset-iff max.coboundedI2 subset-insertI*)
apply *clarsimp*
by (*meson List.finite-set Max-ge finite-imageI finite-insert image-subset-iff max.coboundedI1 subset-insertI*)

lemma *split-fml-satisfies*:
assumes *sat-fml w F*
obtains *w'* **where** *sat-fml w'* (*split-fml k F*)
proof −
obtain *acc' u'* **where**
∗: *fold* (*split-xor k*) (*snd F*) ([], *var-fml F* + *1*) = (*acc'*,*u'*)
by *fastforce*
have *1*:⋀*x*. *x* ∈ *set* (*snd F*) ⟹ *sat-cmsxor w x*
using *assms* **unfolding** *sat-fml-def* **by** *auto*
have *2*:⋀*x*. *x* ∈ *set* (*snd F*) ⟹ *var-lits x* < *var-fml F* + *1*
using *var-lits-var-fml*
by (*meson less-add-one order-le-less-trans*)
from *split-xors-sound*[*OF 1 - - 2* ∗]
obtain *w'* **where**
w': ⋀*x*. *x* < *var-fml F* + *1* ⟹ *w x* = *w' x*
⋀*x*. *x* ∈ *set acc'* ⟹ *sat-cmsxor w' x*
⋀*x*. *x* ∈ *set acc'* ⟹ *var-lits x* < *u'*
using *2* **by** *auto*

have $\bigwedge x.\ x \in set\ (fst\ F) \Longrightarrow sat\text{-}clause\ w'\ x$
by (*metis assms less-add-one order-trans-rules*(*21*) *sat-fml-def sat-lits-same var-lits-var-fml*(*2*) w'(*1*))

then have *sat-fml* w' (*split-fml k F*)
unfolding *split-fml-def Let-def split-xors-def* $*$
by (*auto simp add*: *sat-fml-def* w'(*2*))
thus *?thesis*
using *that* **by** *auto*
qed

lemma *split-fml-sols*:
assumes *sols* (*split-fml k F*) = {}
shows *sols F* = {}
using *assms*
using *split-fml-satisfies* **unfolding** *sols-def*
by (*metis Collect-empty-eq*)

definition *blast-xors* :: *cmsxor list* ⇒ *clause list*
where *blast-xors xors* = *concat* (*map* (λ*x*. *xor-clauses x True*) *xors*)

definition *blast-fml* :: *fml* ⇒ *clause list*
where *blast-fml f* =
fst f @ *blast-xors* (*snd f*)

lemma *sat-clauses-concat*:
sat-clauses w (*concat xs*) ⟷
(∀ *x* ∈ *set xs*. *sat-clauses w x*)
unfolding *sat-clauses-def*
by *auto*

lemma *blast-xors-sound*:
assumes ($\bigwedge x.\ x \in set\ xors \Longrightarrow sat\text{-}cmsxor\ w\ x$)
shows *sat-clauses w* (*blast-xors xors*)
unfolding *blast-xors-def sat-clauses-concat*
by (*auto simp add*: *assms sols-xor-clauses*)

lemma *blast-fml-sound*:
assumes *sat-fml w F*
shows *sat-fml w* (*blast-fml F*,[])
unfolding *blast-fml-def sat-fml-def*
apply *clarsimp*
using *assms blast-xors-sound sat-clauses-def sat-fml-def* **by** *blast*

definition *blast-split-fml* :: *fml* ⇒ *clause list*
where *blast-split-fml f* = *blast-fml* (*split-fml 1 f*)

lemma *blast-split-fml-sols*:
assumes *sols* (*blast-split-fml F*,[]) = {}

shows *sols F = {}*
by (*metis Collect-empty-eq assms blast-fml-sound blast-split-fml-def sols-def split-fml-sols*)

definition *certcheck-blast*::
(*clause list ⇒ bool*) ⇒
fml ⇒ nat list ⇒
real ⇒ real ⇒
((*nat ⇒ bool*) *list* ×
(*nat ⇒* (*nat* × (*nat ⇒ bool*) *list* × (*nat ⇒ bool*) *list*))) ⇒
(*nat ⇒ nat ⇒* (*bool list* × *bool*)) ⇒
String.literal + *nat*
where *certcheck-blast check-unsat F S ε δ m0ms =*
certcheck (*check-unsat* ∘ *blast-split-fml*) *F S ε δ m0ms*

corollary *certcheck-blast-sound*:
assumes ⋀*F*. *check-unsat F ⟹ sols* (*F*, []) = {}
assumes *0 < δ δ < 1*
assumes *0 < ε*
assumes *distinct S*
shows
measure-pmf.prob
(*map-pmf* (λ*r*. *certcheck-blast check-unsat F S ε δ* (*f r*) *r*)
(*random-seed-xors* (*find-t δ*) (*length S*)))
{*c*. ¬ *isl c* ∧
real (*projr c*) ∉
{*real* (*card* (*proj* (*set S*) (*sols F*))) / (*1* + *ε*)..
(*1* + *ε*) ∗ *real* (*card* (*proj* (*set S*) (*sols F*)))}} ≤ *δ*
unfolding *certcheck-blast-def*
apply (*intro CertCheck-CNF-XOR.certcheck-sound*[*OF - assms*(*2*−*5*)])
using *assms*(*1*) **unfolding** *Let-def*
using *blast-split-fml-sols* **by** *auto*

corollary *certcheck-blast-promise-complete*:
assumes ⋀*F*. *check-unsat F ⟹ sols* (*F*, []) = {}
assumes *0 < δ δ < 1*
assumes *0 < ε*
assumes *distinct S*
assumes *r*: ⋀*r*.
r ∈ *set-pmf* (*random-seed-xors* (*find-t δ*) (*length S*)) ⟹
¬*isl* (*certcheck-blast check-unsat F S ε δ* (*f r*) *r*)
shows
measure-pmf.prob
(*map-pmf* (λ*r*. *certcheck-blast check-unsat F S ε δ* (*f r*) *r*)
(*random-seed-xors* (*find-t δ*) (*length S*)))
{*c*. *real* (*projr c*) ∈
{*real* (*card* (*proj* (*set S*) (*sols F*))) / (*1* + *ε*)..
(*1* + *ε*) ∗ *real* (*card* (*proj* (*set S*) (*sols F*)))}} ≥ *1* − *δ*

unfolding *certcheck-blast-def*
apply (*intro CertCheck-CNF-XOR.certcheck-promise-complete*[*OF - assms*(*2*−*5*)])
using *assms*(*1*) **unfolding** *Let-def*
using *blast-split-fml-sols assms*(*6*) **unfolding** *certcheck-blast-def* **by** *auto*

8.2 Export code for a SML implementation.

definition *real-of-int* :: *integer* ⇒ *real*
where *real-of-int n* = *real* (*nat-of-integer n*)

definition *real-mult* :: *real* ⇒ *real* ⇒ *real*
where *real-mult n m* = *n* ∗ *m*

definition *real-div* :: *real* ⇒ *real* ⇒ *real*
where *real-div n m* = *n* / *m*

definition *real-plus* :: *real* ⇒ *real* ⇒ *real*
where *real-plus n m* = *n* + *m*

definition *real-minus* :: *real* ⇒ *real* ⇒ *real*
where *real-minus n m* = *n* − *m*

declare [[*code abort*: *fix-t*]]

export-code
length
nat-of-integer int-of-integer
integer-of-nat integer-of-int
real-of-int real-mult real-div real-plus real-minus
quotient-of

Pos Neg
CertCheck-CNF-XOR.appmc.compute-thresh
find-t certcheck
certcheck-blast
in *SML*

end

References

[1] S. Chakraborty, K. S. Meel, and M. Y. Vardi. Algorithmic improvements in approximate counting for probabilistic inference: From linear to logarithmic SAT calls. In S. Kambhampati, editor, *IJCAI*, pages 3569–3576. IJCAI/AAAI Press, 2016.