

Verification of Functional Binomial Queues

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Abstract. Priority queues are an important data structure and efficient implementations of them are crucial. We implement a functional variant of binomial queues in Isabelle/HOL and show its functional correctness. A verification against an abstract reference specification of priority queues has also been attempted, but could not be achieved to the full extent.

1 Abstract priority queues

1.1 Generic Lemmas

lemma *tl-set*:

distinct q \implies *set (tl q) = set q - {hd q}*
by (*cases q*) *simp-all*

1.2 Type of abstract priority queues

typedef (**overloaded**) (*'a, 'b::linorder*) *pq* =
{xs :: ('a × 'b) list. distinct (map fst xs) ∧ sorted (map snd xs)}
morphisms *alist-of Abs-pq*

proof –

have $\square \in ?pq$ **by** *simp*
then show *?thesis* **by** *blast*

qed

lemma *alist-of-Abs-pq*:

assumes *distinct (map fst xs)*
and *sorted (map snd xs)*
shows *alist-of (Abs-pq xs) = xs*
by (*rule Abs-pq-inverse*) (*simp add: assms*)

lemma [*code abstype*]:

Abs-pq (alist-of q) = q
by (*fact alist-of-inverse*)

lemma *distinct-fst-alist-of* [*simp*]:
 distinct (*map fst (alist-of q)*)
 using *alist-of* [*of q*] **by** *simp*

lemma *distinct-alist-of* [*simp*]:
 distinct (*alist-of q*)
 using *distinct-fst-alist-of* [*of q*] **by** (*simp add: distinct-map*)

lemma *sorted-snd-alist-of* [*simp*]:
 sorted (*map snd (alist-of q)*)
 using *alist-of* [*of q*] **by** *simp*

lemma *alist-of-eqI*:
 alist-of p = alist-of q \implies *p = q*
proof –
 assume *alist-of p = alist-of q*
 then have *Abs-pq (alist-of p) = Abs-pq (alist-of q)* **by** *simp*
 thus *p = q* **by** (*simp add: alist-of-inverse*)
qed

definition *values* :: (*'a, 'b::linorder*) *pq* \Rightarrow *'a list* (*|(-)|*) **where**
 values q = map fst (alist-of q)

definition *priorities* :: (*'a, 'b::linorder*) *pq* \Rightarrow *'b list* (*||(-)||*) **where**
 priorities q = map snd (alist-of q)

lemma *values-set*:
 set |q| = fst ' set (alist-of q)
 by (*simp add: values-def*)

lemma *priorities-set*:
 set ||q|| = snd ' set (alist-of q)
 by (*simp add: priorities-def*)

definition *is-empty* :: (*'a, 'b::linorder*) *pq* \Rightarrow *bool* **where**
 is-empty q \longleftrightarrow *alist-of q = []*

definition *priority* :: (*'a, 'b::linorder*) *pq* \Rightarrow *'a* \Rightarrow *'b option* **where**
 priority q = map-of (alist-of q)

definition *min* :: (*'a, 'b::linorder*) *pq* \Rightarrow *'a* **where**
 min q = fst (hd (alist-of q))

definition *empty* :: (*'a, 'b::linorder*) *pq* **where**
 empty = Abs-pq []

lemma *is-empty-alist-of* [*dest*]:
is-empty *q* \implies *alist-of* *q* = []
by (*simp add: is-empty-def*)

lemma *not-is-empty-alist-of* [*dest*]:
 \neg *is-empty* *q* \implies *alist-of* *q* \neq []
by (*simp add: is-empty-def*)

lemma *alist-of-empty* [*simp, code abstract*]:
alist-of empty = []
by (*simp add: empty-def Abs-pq-inverse*)

lemma *values-empty* [*simp*]:
|*empty*| = []
by (*simp add: values-def*)

lemma *priorities-empty* [*simp*]:
||*empty*|| = []
by (*simp add: priorities-def*)

lemma *values-empty-nothing* [*simp*]:
 $\forall k. k \notin \text{set } |empty|$
by (*simp add: values-def*)

lemma *is-empty-empty*:
is-empty *q* \longleftrightarrow *q* = *empty*
proof (*rule iffI*)
assume *is-empty* *q*
then have *alist-of* *q* = [] **by** (*simp add: is-empty-alist-of*)
then have *Abs-pq* (*alist-of* *q*) = *Abs-pq* [] **by** *simp*
then show *q* = *empty* **by** (*simp add: empty-def alist-of-inverse*)
qed (*simp add: is-empty-def*)

lemma *is-empty-empty-simp* [*simp*]:
is-empty empty
by (*simp add: is-empty-empty*)

lemma *map-snd-alist-of*:
map (*the* \circ *priority* *q*) (*values* *q*) = *map snd* (*alist-of* *q*)
by (*auto simp add: values-def priority-def*)

lemma *image-snd-alist-of*:
the ' *priority* *q* ' *set* (*values* *q*) = *snd* ' *set* (*alist-of* *q*)
proof –

from *map-snd-alist-of* [*of q*]
have *set (map (the ∘ priority q) (values q)) = set (map snd (alist-of q))*
by (*simp only*:)
then show *?thesis* **by** (*simp add: image-comp*)
qed

lemma *Min-snd-alist-of*:
assumes \neg *is-empty q*
shows *Min (snd ‘ set (alist-of q)) = snd (hd (alist-of q))*
proof –
from *assms* **obtain** *ps p* **where** *q: map snd (alist-of q) = p # ps*
by (*cases map snd (alist-of q)*) *auto*
then have *hd (map snd (alist-of q)) = p* **by** *simp*
with *assms* **have** *p: snd (hd (alist-of q)) = p* **by** (*auto simp add: hd-map*)
have *sorted (map snd (alist-of q))* **by** *simp*
with *q* **have** *sorted (p # ps)* **by** *simp*
then have $\forall p' \in \text{set } ps. p' \geq p$ **by** (*simp*)
then have *Min (set (p # ps)) = p* **by** (*auto intro: Min-eqI*)
with *p q* **have** *Min (set (map snd (alist-of q))) = snd (hd (alist-of q))*
by *simp*
then show *?thesis* **by** *simp*
qed

lemma *priority-fst*:
assumes *xp ∈ set (alist-of q)*
shows *priority q (fst xp) = Some (snd xp)*
using *assms* **by** (*simp add: priority-def*)

lemma *priority-Min*:
assumes \neg *is-empty q*
shows *priority q (min q) = Some (Min (the ‘ priority q ‘ set (values q)))*
using *assms*
by (*auto simp add: min-def image-snd-alist-of Min-snd-alist-of priority-fst*)

lemma *priority-Min-priorities*:
assumes \neg *is-empty q*
shows *priority q (min q) = Some (Min (set ||q||))*
using *assms*
by (*simp add: priority-Min image-snd-alist-of priorities-def*)

definition *push* :: *'a ⇒ 'b::linorder ⇒ ('a, 'b) pq ⇒ ('a, 'b) pq* **where**
push k p q = Abs-pq (if k ∉ set (values q)
then insort-key snd (k, p) (alist-of q)
else alist-of q)

lemma *Min-snd-hd*:

$q \neq [] \implies \text{sorted } (\text{map } \text{snd } q) \implies \text{Min } (\text{snd } ' \text{ set } q) = \text{snd } (\text{hd } q)$

proof (*induct* q)

case (*Cons* x xs) **then show** *?case* **by** (*cases* xs) (*auto simp add: ord-class.min-def*)
qed *simp*

lemma *hd-construct*:

assumes $\neg \text{is-empty } q$

shows $\text{hd } (\text{alist-of } q) = (\text{min } q, \text{the } (\text{priority } q (\text{min } q)))$

proof –

from *assms* **have** $\text{the } (\text{priority } q (\text{min } q)) = \text{snd } (\text{hd } (\text{alist-of } q))$

using *Min-snd-hd* [*of* $\text{alist-of } q$]

by (*auto simp add: priority-Min-priorities priorities-def*)

then show *?thesis* **by** (*simp add: min-def*)

qed

lemma *not-in-first-image*:

$x \notin \text{fst } ' s \implies (x, p) \notin s$

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

lemma *alist-of-push* [*simp, code abstract*]:

$\text{alist-of } (\text{push } k \ p \ q) =$

$(\text{if } k \notin \text{set } (\text{values } q) \text{ then } \text{insort-key } \text{snd } (k, p) (\text{alist-of } q) \text{ else } \text{alist-of } q)$

using *distinct-fst-alist-of* [*of* q]

by (*auto simp add: distinct-map set-insort-key distinct-insort not-in-first-image push-def values-def sorted-insort-key intro: alist-of-Abs-pq*)

lemma *push-values* [*simp*]:

$\text{set } |\text{push } k \ p \ q| = \text{set } |q| \cup \{k\}$

by (*auto simp add: values-def set-insort-key*)

lemma *push-priorities* [*simp*]:

$k \notin \text{set } |q| \implies \text{set } \|\text{push } k \ p \ q\| = \text{set } \|q\| \cup \{p\}$

$k \in \text{set } |q| \implies \text{set } \|\text{push } k \ p \ q\| = \text{set } \|q\|$

by (*auto simp add: priorities-def set-insort-key*)

lemma *not-is-empty-push* [*simp*]:

$\neg \text{is-empty } (\text{push } k \ p \ q)$

by (*auto simp add: values-def is-empty-def*)

lemma *push-commute*:

assumes $a \neq b$ **and** $v \neq w$

shows $\text{push } w \ b (\text{push } v \ a \ q) = \text{push } v \ a (\text{push } w \ b \ q)$

using *assms* **by** (*auto intro!: alist-of-eqI insort-key-left-comm*)

definition *remove-min* :: ('a, 'b::linorder) pq \Rightarrow ('a, 'b::linorder) pq **where**
remove-min q = (if is-empty q then empty else Abs-pq (tl (alist-of q)))

lemma *alift-of-remove-min-if* [code abstract]:
 alist-of (remove-min q) = (if is-empty q then [] else tl (alist-of q))
by (auto simp add: remove-min-def map-tl sorted-tl distinct-tl alist-of-Abs-pq)

lemma *remove-min-empty* [simp]:
 is-empty q \Longrightarrow remove-min q = empty
by (simp add: remove-min-def)

lemma *alist-of-remove-min* [simp]:
 \neg is-empty q \Longrightarrow alist-of (remove-min q) = tl (alist-of q)
by (simp add: alift-of-remove-min-if)

lemma *values-remove-min* [simp]:
 \neg is-empty q \Longrightarrow values (remove-min q) = tl (values q)
by (simp add: values-def map-tl)

lemma *set-alist-of-remove-min*:
 \neg is-empty q \Longrightarrow set (alist-of (remove-min q)) =
 set (alist-of q) - {(min q, the (priority q (min q)))}
by (simp add: tl-set hd-construct)

definition *pop* :: ('a, 'b::linorder) pq \Rightarrow ('a \times ('a, 'b) pq) option **where**
pop q = (if is-empty q then None else Some (min q, remove-min q))

lemma *pop-simps* [simp]:
 is-empty q \Longrightarrow pop q = None
 \neg is-empty q \Longrightarrow pop q = Some (min q, remove-min q)
by (simp-all add: pop-def)

hide-const (open) Abs-pq alist-of values priority empty is-empty push min pop

no-notation

PQ.values (|(-)|)
and *PQ.priorities* (||(-)||)

2 Functional Binomial Queues

2.1 Type definition and projections

datatype ('a, 'b) bintree = Node 'a 'b ('a, 'b) bintree list

primrec *priority* :: ('a, 'b) bintree \Rightarrow 'a **where**

priority (Node a - -) = a

primrec *val* :: ('a, 'b) bintree \Rightarrow 'b **where**
val (Node - v -) = v

primrec *children* :: ('a, 'b) bintree \Rightarrow ('a, 'b) bintree list **where**
children (Node - - ts) = ts

type-synonym ('a, 'b) binqueue = ('a, 'b) bintree option list

lemma *binqueue-induct* [case-names Empty None Some, induct type: binqueue]:

assumes *P* []

and $\bigwedge xs. P\ xs \Longrightarrow P\ (None\ \#\ xs)$

and $\bigwedge x\ xs. P\ xs \Longrightarrow P\ (Some\ x\ \#\ xs)$

shows *P xs*

using *assms*

proof (*induct xs*)

case *Nil*

then show ?case by *simp*

next

case (*Cons x xs*)

then show ?case by (*cases x*) *simp-all*

qed

Terminology:

- values *v*, *w* or *v1*, *v2*
- priorities *a*, *b* or *a1*, *a2*
- bintrees *t*, *r* or *t1*, *t2*
- bintree lists *ts*, *rs* or *ts1*, *ts2*
- binqueue element *x*, *y* or *x1*, *x2*
- binqueues = binqueue element lists *xs*, *ys* or *xs1*, *xs2*
- abstract priority queues *q*, *p* or *q1*, *q2*

2.2 Binomial queue properties

Binomial tree property

inductive *is-bintree-list* :: nat \Rightarrow ('a, 'b) bintree list \Rightarrow bool **where**

is-bintree-list-Nil [*simp*]: *is-bintree-list* 0 []

| *is-bintree-list-Cons*: *is-bintree-list* l ts \Longrightarrow *is-bintree-list* l (*children* t)
 \Longrightarrow *is-bintree-list* (Suc l) (t # ts)

abbreviation (*input*) *is-bintree* k t \equiv *is-bintree-list* k (*children* t)

lemma *is-bintree-list-triv* [simp]:
is-bintree-list 0 *ts* \longleftrightarrow *ts* = []
is-bintree-list *l* [] \longleftrightarrow *l* = 0
by (auto intro: *is-bintree-list.intros* elim: *is-bintree-list.cases*)

lemma *is-bintree-list-simp* [simp]:
is-bintree-list (Suc *l*) (*t* # *ts*) \longleftrightarrow
is-bintree-list *l* (children *t*) \wedge *is-bintree-list* *l* *ts*
by (auto intro: *is-bintree-list.intros* elim: *is-bintree-list.cases*)

lemma *is-bintree-list-length* [simp]:
is-bintree-list *l* *ts* \implies length *ts* = *l*
by (erule *is-bintree-list.induct*) simp-all

lemma *is-bintree-list-children-last*:
assumes *is-bintree-list* *l* *ts* **and** *ts* \neq []
shows children (last *ts*) = []
using *assms* **by** induct auto

lemma *is-bintree-children-length-desc*:
assumes *is-bintree-list* *l* *ts*
shows map (length \circ children) *ts* = rev [0..*l*]
using *assms* **by** (induct *ts*) simp-all

Heap property

inductive *is-heap-list* :: 'a::linorder \Rightarrow ('a, 'b) bintree list \Rightarrow bool **where**
is-heap-list-Nil: *is-heap-list* *h* []
| *is-heap-list-Cons*: *is-heap-list* *h* *ts* \implies *is-heap-list* (priority *t*) (children *t*)
 \implies (priority *t*) \geq *h* \implies *is-heap-list* *h* (*t* # *ts*)

abbreviation (input) *is-heap* *t* \equiv *is-heap-list* (priority *t*) (children *t*)

lemma *is-heap-list-simps* [simp]:
is-heap-list *h* [] \longleftrightarrow True
is-heap-list *h* (*t* # *ts*) \longleftrightarrow
is-heap-list *h* *ts* \wedge *is-heap-list* (priority *t*) (children *t*) \wedge priority *t* \geq *h*
by (auto intro: *is-heap-list.intros* elim: *is-heap-list.cases*)

lemma *is-heap-list-append-dest* [dest]:
is-heap-list *l* (*ts*@*rs*) \implies *is-heap-list* *l* *ts*
is-heap-list *l* (*ts*@*rs*) \implies *is-heap-list* *l* *rs*
by (induct *ts*) (auto intro: *is-heap-list.intros* elim: *is-heap-list.cases*)

lemma *is-heap-list-rev*:

is-heap-list l $ts \implies is-heap-list$ l (*rev* ts)
by (*induct* ts *rule: rev-induct*) *auto*

lemma *is-heap-children-larger*:
is-heap $t \implies \forall x \in set$ (*children* t). *priority* $x \geq priority$ t
by (*erule is-heap-list.induct*) *simp-all*

lemma *is-heap-Min-children-larger*:
is-heap $t \implies children$ $t \neq [] \implies$
priority $t \leq Min$ (*priority* ‘ set (*children* t))
by (*simp add: is-heap-children-larger*)

Combination of both: biqueue property

inductive *is-biqueue* :: $nat \Rightarrow ('a::linorder, 'b)$ *biqueue* $\Rightarrow bool$ **where**
Empty: is-biqueue $l []$
| *None: is-biqueue* (*Suc* l) $xs \implies is-biqueue$ l (*None* # xs)
| *Some: is-biqueue* (*Suc* l) $xs \implies is-bintree$ l t
 $\implies is-heap$ $t \implies is-biqueue$ l (*Some* t # xs)

lemma *is-biqueue-simp* [*simp*]:
is-biqueue $l [] \longleftrightarrow True$
is-biqueue l (*Some* t # xs) \longleftrightarrow
is-bintree l $t \wedge is-heap$ $t \wedge is-biqueue$ (*Suc* l) xs
is-biqueue l (*None* # xs) $\longleftrightarrow is-biqueue$ (*Suc* l) xs
by (*auto intro: is-biqueue.intros elim: is-biqueue.cases*)

lemma *is-biqueue-trans*:
is-biqueue l (x # xs) $\implies is-biqueue$ (*Suc* l) xs
by (*cases* x) *simp-all*

lemma *is-biqueue-head*:
is-biqueue l (x # xs) $\implies is-biqueue$ l [x]
by (*cases* x) *simp-all*

lemma *is-biqueue-append*:
is-biqueue l $xs \implies is-biqueue$ (*length* $xs + l$) $ys \implies is-biqueue$ l (xs @ ys)
by (*induct* xs *arbitrary: l*) (*auto intro: is-biqueue.intros elim: is-biqueue.cases*)

lemma *is-biqueue-append-dest* [*dest*]:
is-biqueue l (xs @ ys) $\implies is-biqueue$ l xs
by (*induct* xs *arbitrary: l*) (*auto intro: is-biqueue.intros elim: is-biqueue.cases*)

lemma *is-biqueue-children*:
assumes *is-bintree-list* l ts

and *is-heap-list* t ts
shows *is-bingueue* 0 (*map* *Some* (*rev* ts))
using *assms* **by** (*induct* ts) (*auto simp add: is-bingueue-append*)

lemma *is-bingueue-select*:
is-bingueue l $xs \implies \text{Some } t \in \text{set } xs \implies \exists k. \text{is-bintree } k \ t \wedge \text{is-heap } t$
by (*induct* xs *arbitrary: l*) (*auto intro: is-bingueue.intros elim: is-bingueue.cases*)

Normalized representation

inductive *normalized* :: ('a, 'b) *bingueue* \Rightarrow *bool* **where**
normalized-Nil: *normalized* []
| *normalized-single*: *normalized* [Some t]
| *normalized-append*: $xs \neq [] \implies \text{normalized } xs \implies \text{normalized } (ys @ xs)$

lemma *normalized-last-not-None*:
— sometimes the inductive definition might work better
normalized $xs \longleftrightarrow xs = [] \vee \text{last } xs \neq \text{None}$

proof
assume *normalized* xs
then show $xs = [] \vee \text{last } xs \neq \text{None}$
by (*rule* *normalized.induct*) *simp-all*
next
assume *: $xs = [] \vee \text{last } xs \neq \text{None}$
show *normalized* xs **proof** (*cases* xs *rule: rev-cases*)
case *Nil* **then show** *?thesis* **by** (*simp add: normalized.intros*)
next
case (*snoc* ys x) **with** * **obtain** t **where** $\text{last } xs = \text{Some } t$ **by** *auto*
with *snoc* **have** $xs = ys @ [\text{Some } t]$ **by** *simp*
then show *?thesis* **by** (*simp add: normalized.intros*)
qed
qed

lemma *normalized-simps* [*simp*]:
normalized [] $\longleftrightarrow \text{True}$
normalized (*Some* t # xs) $\longleftrightarrow \text{normalized } xs$
normalized (*None* # xs) $\longleftrightarrow xs \neq [] \wedge \text{normalized } xs$
by (*simp-all add: normalized-last-not-None*)

lemma *normalized-map-Some* [*simp*]:
normalized (*map* *Some* xs)
by (*induct* xs) *simp-all*

lemma *normalized-Cons*:
normalized ($x \# xs$) $\implies \text{normalized } xs$

by (auto simp add: normalized-last-not-None)

lemma *normalized-append*:

normalized xs \implies *normalized ys* \implies *normalized (xs@ys)*

by (cases ys) (simp-all add: normalized-last-not-None)

lemma *normalized-not-None*:

normalized xs \implies *set xs* \neq {None}

by (induct xs) (auto simp add: normalized-Cons [of - ts] dest: subset-singletonD)

primrec *normalize'* :: ('a, 'b) *binqueue* \Rightarrow ('a, 'b) *binqueue* **where**

normalize' [] = []

| *normalize'* (x # xs) =

(case x of None \Rightarrow *normalize'* xs | Some t \Rightarrow (x # xs))

definition *normalize* :: ('a, 'b) *binqueue* \Rightarrow ('a, 'b) *binqueue* **where**

normalize xs = *rev (normalize' (rev xs))*

lemma *normalized-normalize*:

normalized (normalize xs)

proof (induct xs rule: rev-induct)

case (snoc y ys) **then show** ?case

by (cases y) (simp-all add: normalized-last-not-None normalize-def)

qed (simp add: normalize-def)

lemma *is-binqueue-normalize*:

is-binqueue l xs \implies *is-binqueue l (normalize xs)*

unfolding *normalize-def*

by (induct xs arbitrary: l rule: rev-induct) (auto split: option.split)

2.3 Operations

Adding data

definition *merge* :: ('a::linorder, 'b) *bintree* \Rightarrow ('a, 'b) *bintree* \Rightarrow ('a, 'b) *bintree*

where

merge t1 t2 = (if *priority t1* < *priority t2*

then *Node (priority t1) (val t1) (t2 # children t1)*

else *Node (priority t2) (val t2) (t1 # children t2)*)

lemma *is-bintree-list-merge*:

assumes *is-bintree l t1 is-bintree l t2*

shows *is-bintree (Suc l) (merge t1 t2)*

using *assms* **by** (simp add: merge-def)

```

lemma is-heap-merge:
  assumes is-heap t1 is-heap t2
  shows is-heap (merge t1 t2)
  using assms by (auto simp add: merge-def)

fun
  add :: ('a::linorder, 'b) bintree option  $\Rightarrow$  ('a, 'b) binqueue  $\Rightarrow$  ('a, 'b) binqueue
where
  add None xs = xs
| add (Some t) [] = [Some t]
| add (Some t) (None # xs) = Some t # xs
| add (Some t) (Some r # xs) = None # add (Some (merge t r)) xs

lemma add-Some-not-Nil [simp]:
  add (Some t) xs  $\neq$  []
  by (induct Some t xs rule: add.induct) simp-all

lemma normalized-add:
  assumes normalized xs
  shows normalized (add x xs)
  using assms by (induct xs rule: add.induct) simp-all

lemma is-binqueue-add-None:
  assumes is-binqueue l xs
  shows is-binqueue l (add None xs)
  using assms by simp

lemma is-binqueue-add-Some:
  assumes is-binqueue l xs
  and is-bintree l t
  and is-heap t
  shows is-binqueue l (add (Some t) xs)
  using assms by (induct xs arbitrary: t) (simp-all add: is-bintree-list-merge
is-heap-merge)

function
  meld :: ('a::linorder, 'b) binqueue  $\Rightarrow$  ('a, 'b) binqueue  $\Rightarrow$  ('a, 'b) binqueue
where
  meld [] ys = ys
| meld xs [] = xs
| meld (None # xs) (y # ys) = y # meld xs ys
| meld (x # xs) (None # ys) = x # meld xs ys
| meld (Some t # xs) (Some r # ys) =
  None # add (Some (merge t r)) (meld xs ys)
by pat-completeness auto termination by lexicographic-order

```

```

lemma meld-singleton-add [simp]:
  meld [Some t] xs = add (Some t) xs
  by (induct Some t xs rule: add.induct) simp-all

lemma nonempty-meld [simp]:
  xs ≠ [] ⇒ meld xs ys ≠ []
  ys ≠ [] ⇒ meld xs ys ≠ []
  by (induct xs ys rule: meld.induct) auto

lemma nonempty-meld-commute:
  meld xs ys ≠ [] ⇒ meld xs ys ≠ []
  by (induct xs ys rule: meld.induct) auto

lemma is-binnacle-meld:
  assumes is-binnacle l xs
  and is-binnacle l ys
  shows is-binnacle l (meld xs ys)
using assms
proof (induct xs ys arbitrary: l rule: meld.induct)
  fix xs ys :: ('a, 'b) binnacle
  fix y :: ('a, 'b) bintree option
  fix l :: nat
  assume  $\bigwedge l. \textit{is-binnacle l xs} \Rightarrow \textit{is-binnacle l ys}$ 
    ⇒ is-binnacle l (meld xs ys)
    and is-binnacle l (None # xs)
    and is-binnacle l (y # ys)
  then show is-binnacle l (meld (None # xs) (y # ys)) by (cases y) simp-all
next
  fix xs ys :: ('a, 'b) binnacle
  fix x :: ('a, 'b) bintree option
  fix l :: nat
  assume  $\bigwedge l. \textit{is-binnacle l xs} \Rightarrow \textit{is-binnacle l ys}$ 
    ⇒ is-binnacle l (meld xs ys)
    and is-binnacle l (x # xs)
    and is-binnacle l (None # ys)
  then show is-binnacle l (meld (x # xs) (None # ys)) by (cases x) simp-all
qed (simp-all add: is-bintree-list-merge is-heap-merge is-binnacle-add-Some)

lemma normalized-meld:
  assumes normalized xs
  and normalized ys
  shows normalized (meld xs ys)
using assms
proof (induct xs ys rule: meld.induct)

```

```

fix xs ys :: ('a, 'b) binqueue
fix y :: ('a, 'b) bintree option
assume normalized xs  $\implies$  normalized ys  $\implies$  normalized (meld xs ys)
  and normalized (None # xs)
  and normalized (y # ys)
then show normalized (meld (None # xs) (y # ys)) by (cases y) simp-all
next
fix xs ys :: ('a, 'b) binqueue
fix x :: ('a, 'b) bintree option
assume normalized xs  $\implies$  normalized ys  $\implies$  normalized (meld xs ys)
  and normalized (x # xs)
  and normalized (None # ys)
then show normalized (meld (x # xs) (None # ys)) by (cases x) simp-all
qed (simp-all add: normalized-add)

```

lemma *normalized-meld-weak*:

```

assumes normalized xs
and length ys  $\leq$  length xs
shows normalized (meld xs ys)
using assms
proof (induct xs ys rule: meld.induct)
fix xs ys :: ('a, 'b) binqueue
fix y :: ('a, 'b) bintree option
assume normalized xs  $\implies$  length ys  $\leq$  length xs  $\implies$  normalized (meld xs ys)
  and normalized (None # xs)
  and length (y # ys)  $\leq$  length (None # xs)
then show normalized (meld (None # xs) (y # ys)) by (cases y) simp-all
next
fix xs ys :: ('a, 'b) binqueue
fix x :: ('a, 'b) bintree option
assume normalized xs  $\implies$  length ys  $\leq$  length xs  $\implies$  normalized (meld xs ys)
  and normalized (x # xs)
  and length (None # ys)  $\leq$  length (x # xs)
then show normalized (meld (x # xs) (None # ys)) by (cases x) simp-all
qed (simp-all add: normalized-add)

```

definition *least* :: 'a::linorder option \Rightarrow 'a option \Rightarrow 'a option **where**

```

least x y = (case x of
  None  $\Rightarrow$  y
  | Some x'  $\Rightarrow$  (case y of
    None  $\Rightarrow$  x
    | Some y'  $\Rightarrow$  if x' <= y' then x else y))

```

lemma *least-simps* [*simp*, *code*]:

```

least None x = x

```

$least\ x\ None = x$
 $least\ (Some\ x')\ (Some\ y') = (if\ x' \leq y'\ then\ Some\ x'\ else\ Some\ y')$
unfolding *least-def* **by** (*simp-all*) (*cases x, simp-all*)

lemma *least-split*:
assumes $least\ x\ y = Some\ z$
shows $x = Some\ z \vee y = Some\ z$
using *assms* **proof** (*cases x*)
case ($Some\ x'$) **with** *assms* **show** *?thesis* **by** (*cases y*) (*simp-all add: eq-commute*)
qed *simp*

interpretation *least: semilattice least* **proof**
qed (*auto simp add: least-def split: option.split*)

definition $min :: ('a::linorder, 'b) binqueue \Rightarrow 'a\ option$ **where**
 $min\ xs = fold\ least\ (map\ (map-option\ priority)\ xs)\ None$

lemma *min-simps* [*simp*]:
 $min\ [] = None$
 $min\ (None\ \#\ xs) = min\ xs$
 $min\ (Some\ t\ \#\ xs) = least\ (Some\ (priority\ t))\ (min\ xs)$
by (*simp-all add: min-def fold-commute-apply [symmetric]*)
fun-eq-iff least.left-commute del: least-simps

lemma [*code*]:
 $min\ xs = fold\ (\lambda\ x.\ least\ (map-option\ priority\ x))\ xs\ None$
by (*simp add: min-def fold-map o-def*)

lemma *min-single*:
 $min\ [x] = Some\ a \implies priority\ (the\ x) = a$
 $min\ [x] = None \implies x = None$
by (*auto simp add: min-def*)

lemma *min-Some-not-None*:
 $min\ (Some\ t\ \#\ xs) \neq None$
by (*cases min xs simp-all*)

lemma *min-None-trans*:
assumes $min\ (x\ \#\ xs) = None$
shows $min\ xs = None$
using *assms* **proof** (*cases x*)
case *None* **with** *assms* **show** *?thesis* **by** *simp*
next
case ($Some\ t$) **with** *assms* **show** *?thesis* **by** (*simp only: min-Some-not-None*)
qed

```

lemma min-None-None:
  min xs = None  $\longleftrightarrow$  xs = []  $\vee$  set xs = {None}
proof (rule iffI)
  have splitQ:  $\bigwedge$  xs. xs  $\subseteq$  {None}  $\implies$  xs = {}  $\vee$  xs = {None} by auto

  assume min xs = None
  then have set xs  $\subseteq$  {None}
  proof (induct xs)
    case (None ys) thus ?case using min-None-trans[of - ys] by simp-all
  next
    case (Some t ys) thus ?case using min-Some-not-None[of t ys] by simp
  qed simp

  with splitQ show xs = []  $\vee$  set xs = {None} by auto
next
  show xs = []  $\vee$  set xs = {None}  $\implies$  min xs = None
    by (induct xs) (auto dest: subset-singletonD)
qed

lemma normalized-min-not-None:
  normalized xs  $\implies$  xs  $\neq$  []  $\implies$  min xs  $\neq$  None
  by (simp add: min-None-None normalized-not-None)

lemma min-is-min:
  assumes normalized xs
  and xs  $\neq$  []
  and min xs = Some a
  shows  $\forall x \in$  set xs. x = None  $\vee$  a  $\leq$  priority (the x)
using assms proof (induct xs arbitrary: a rule: binqueue-induct)
  case (Some t ys) thus ?case
  proof (cases ys = [])
    case False
      with Some have N: normalized ys using normalized-Cons[of - ys] by simp
      with  $\langle$ ys  $\neq$  [] $\rangle$  have min ys  $\neq$  None
        by (simp add: normalized-min-not-None)
      then obtain a' where oa': min ys = Some a' by auto
      with Some N False
        have  $\forall y \in$  set ys. y = None  $\vee$  a'  $\leq$  priority (the y) by simp

      with Some oa' show ?thesis
        by (cases a'  $\leq$  priority t) (auto simp add: least commute)
    qed simp
  qed simp-all

```


lemma *min-exists*:
assumes $\text{min } xs = \text{Some } a$
shows $\text{Some } a \in \text{map-option priority } \text{' set } xs$
proof (*rule ccontr*)
assume $\text{Some } a \notin \text{map-option priority } \text{' set } xs$
then have $\forall x \in \text{set } xs. x = \text{None} \vee \text{priority } (\text{the } x) \neq a$ **by** (*induct xs*) *auto*
then have $\text{min } xs \neq \text{Some } a$
proof (*induct xs arbitrary: a*)
case (*Some t ys*)
hence $\text{priority } t \neq a$ **and** $\text{min } ys \neq \text{Some } a$ **by** *simp-all*
show *?case*
proof (*rule ccontr, simp*)
assume $\text{least } (\text{Some } (\text{priority } t)) (\text{min } ys) = \text{Some } a$
hence $\text{Some } (\text{priority } t) = \text{Some } a \vee \text{min } ys = \text{Some } a$ **by** (*rule least-split*)
with $\langle \text{min } ys \neq \text{Some } a \rangle$ **have** $\text{priority } t = a$ **by** *simp*
with $\langle \text{priority } t \neq a \rangle$ **show** *False* **by** *simp*
qed
qed *simp-all*
with *assms* **show** *False* **by** *simp*
qed

primrec *find* :: $\text{'a}::\text{linorder} \Rightarrow (\text{'a}, \text{'b}) \text{binqueue} \Rightarrow (\text{'a}, \text{'b}) \text{bintree option}$ **where**
find a [] = None
 $\text{find } a (x\#xs) = (\text{case } x \text{ of } \text{None} \Rightarrow \text{find } a \text{ } xs$
 $\quad | \text{Some } t \Rightarrow \text{if } \text{priority } t = a \text{ then } \text{Some } t \text{ else } \text{find } a \text{ } xs)$

declare *find.simps* [*simp del*]

lemma *find-simps* [*simp, code*]:
 $\text{find } a [] = \text{None}$
 $\text{find } a (\text{None} \# xs) = \text{find } a \text{ } xs$
 $\text{find } a (\text{Some } t \# xs) = (\text{if } \text{priority } t = a \text{ then } \text{Some } t \text{ else } \text{find } a \text{ } xs)$
by (*simp-all add: find-def*)

lemma *find-works*:
assumes $\text{Some } a \in \text{set } (\text{map } (\text{map-option priority}) \text{ } xs)$
shows $\exists t. \text{find } a \text{ } xs = \text{Some } t \wedge \text{priority } t = a$
using *assms* **by** (*induct xs*) *auto*

lemma *find-works-not-None*:
 $\text{Some } a \in \text{set } (\text{map } (\text{map-option priority}) \text{ } xs) \Longrightarrow \text{find } a \text{ } xs \neq \text{None}$
by (*drule find-works*) *auto*

lemma *find-None*:
 $\text{find } a \text{ } xs = \text{None} \Longrightarrow \text{Some } a \notin \text{set } (\text{map } (\text{map-option priority}) \text{ } xs)$

by (auto simp add: find-works-not-None)

lemma *find-exist*:

find a xs = Some t \implies Some t \in set xs

by (induct xs) (simp-all add: eq-commute)

definition *find-min* :: ('a::linorder, 'b) binqueue \implies ('a, 'b) bintree option **where**

find-min xs = (case min xs of None \implies None | Some a \implies find a xs)

lemma *find-min-simps* [simp]:

find-min [] = None

find-min (None # xs) = find-min xs

by (auto simp add: find-min-def split: option.split)

lemma *find-min-single*:

find-min [x] = x

by (cases x) (auto simp add: find-min-def)

lemma *min-eq-find-min-None*:

min xs = None \longleftrightarrow find-min xs = None

proof (rule iffI)

show *min xs = None \implies find-min xs = None*

by (simp add: find-min-def)

next

assume *: *find-min xs = None*

show *min xs = None*

proof (rule ccontr)

assume *min xs \neq None*

then obtain *a where min xs = Some a by auto*

hence *find-min xs \neq None*

by (simp add: find-min-def min-exists find-works-not-None)

with * **show** *False by simp*

qed

qed

lemma *min-eq-find-min-Some*:

min xs = Some a \longleftrightarrow (\exists t. find-min xs = Some t \wedge priority t = a)

proof (rule iffI)

show *D1: \bigwedge a. min xs = Some a*

\implies (\exists t. find-min xs = Some t \wedge priority t = a)

by (simp add: find-min-def find-works min-exists)

assume *: \exists t. find-min xs = Some t \wedge priority t = a

show *min xs = Some a*

```

proof (rule ccontr)
  assume  $\text{min } xs \neq \text{Some } a$  thus False
  proof (cases  $\text{min } xs$ )
    case None
      hence  $\text{find-min } xs = \text{None}$  by (simp only: min-eq-find-min-None)
      with * show False by simp
    next
      case (Some b)
      with  $\langle \text{min } xs \neq \text{Some } a \rangle$  have  $a \neq b$  by simp
      with * Some show False using D1 by auto
  qed
qed
qed

```

```

lemma find-min-exist:
  assumes  $\text{find-min } xs = \text{Some } t$ 
  shows  $t \in \text{set } xs$ 
proof -
  from assms have  $\text{min } xs \neq \text{None}$  by (simp add: min-eq-find-min-None)
  with assms show ?thesis by (auto simp add: find-min-def find-exist)
qed

```

```

lemma find-min-is-min:
  assumes normalized xs
  and  $xs \neq []$ 
  and  $\text{find-min } xs = \text{Some } t$ 
  shows  $\forall x \in \text{set } xs. x = \text{None} \vee (\text{priority } t) \leq \text{priority } (x)$ 
  using assms by (simp add: min-eq-find-min-Some min-is-min)

```

```

lemma normalized-find-min-exists:
   $\text{normalized } xs \implies xs \neq [] \implies \exists t. \text{find-min } xs = \text{Some } t$ 
by (drule normalized-min-not-None) (simp-all add: min-eq-find-min-None)

```

```

primrec
   $\text{match} :: 'a::\text{linorder} \Rightarrow ('a, 'b) \text{bintree option} \Rightarrow ('a, 'b) \text{bintree option}$ 
where
   $\text{match } a \text{ None} = \text{None}$ 
  |  $\text{match } a (\text{Some } t) = (\text{if } \text{priority } t = a \text{ then } \text{None} \text{ else } \text{Some } t)$ 

```

```

definition delete-min :: ('a::linorder, 'b) binqueue  $\Rightarrow$  ('a, 'b) binqueue where
   $\text{delete-min } xs = (\text{case } \text{find-min } xs$ 
    of Some (Node a v ts)  $\Rightarrow$ 
       $\text{normalize } (\text{meld } (\text{map } \text{Some } (\text{rev } ts)) (\text{map } (\text{match } a) xs))$ 
    | None  $\Rightarrow [])$ 

```

lemma *delete-min-empty* [simp]:

delete-min [] = []
by (simp add: delete-min-def)

lemma *delete-min-nonempty* [simp]:

normalized xs \implies *xs* \neq [] \implies *find-min xs* = *Some t*
 \implies *delete-min xs* = *normalize*
(*meld* (*map Some* (*rev* (*children t*))) (*map* (*match* (*priority t*) *xs*))
unfolding *delete-min-def* **by** (*cases t*) *simp*

lemma *is-binqueue-delete-min*:

assumes *is-binqueue* 0 *xs*
shows *is-binqueue* 0 (*delete-min xs*)

proof (*cases find-min xs*)

case (*Some t*)
from *assms* **have** *is-binqueue* 0 (*map* (*match* (*priority t*) *xs*)
by (*induct xs*) *simp-all*

moreover

from *Some* **have** *Some t* \in *set xs* **by** (*rule find-min-exist*)
with *assms* **have** $\exists l.$ *is-bintree l t* **and** *is-heap t*
using *is-binqueue-select*[*of* 0 *xs t*] **by** *auto*
with *assms* **have** *is-binqueue* 0 (*map Some* (*rev* (*children t*)))
by (*auto simp add: is-binqueue-children*)

ultimately show *?thesis* **using** *Some*

by (*auto simp add: is-binqueue-meld delete-min-def is-binqueue-normalize*
split: bintree.split)

qed (*simp add: delete-min-def*)

lemma *normalized-delete-min*:

normalized (*delete-min xs*)
by (*cases find-min xs*)
(*auto simp add: delete-min-def normalized-normalize split: bintree.split*)

Dedicated grand unified operation for generated program

definition

meld' :: ('a, 'b) *bintree option* \Rightarrow ('a::*linorder*, 'b) *binqueue*
 \Rightarrow ('a, 'b) *binqueue* \Rightarrow ('a, 'b) *binqueue*

where

meld' *z xs ys* = *add z* (*meld xs ys*)

lemma [*code*]:

add z xs = *meld'* *z* [] *xs*

meld xs ys = meld' None xs ys
by (*simp-all add: meld'-def*)

lemma [*code*]:

meld' z (Some t # xs) (Some r # ys) =
z # (meld' (Some (merge t r)) xs ys)
meld' (Some t) (Some r # xs) (None # ys) =
None # (meld' (Some (merge t r)) xs ys)
meld' (Some t) (None # xs) (Some r # ys) =
None # (meld' (Some (merge t r)) xs ys)
meld' None (x # xs) (None # ys) = x # (meld' None xs ys)
meld' None (None # xs) (y # ys) = y # (meld' None xs ys)
meld' z (None # xs) (None # ys) = z # (meld' None xs ys)
meld' z xs [] = meld' z [] xs
meld' z [] (y # ys) = meld' None [z] (y # ys)
meld' (Some t) [] ys = meld' None [Some t] ys
meld' None [] ys = ys
by (*simp add: meld'-def | cases z*)+

Interface operations

abbreviation (*input*) *empty* :: ('a,'b) *binqueue* **where**
empty ≡ []

definition

insert :: 'a::linorder ⇒ 'b ⇒ ('a, 'b) *binqueue* ⇒ ('a, 'b) *binqueue*
where

insert a v xs = add (Some (Node a v [])) xs

lemma *insert-simps* [*simp*]:

insert a v [] = [Some (Node a v [])]
insert a v (None # xs) = Some (Node a v []) # xs
insert a v (Some t # xs) = None # add (Some (merge (Node a v []) t)) xs
by (*simp-all add: insert-def*)

lemma *is-binqueue-insert*:

is-binqueue 0 xs ⇒ is-binqueue 0 (insert a v xs)
by (*simp add: is-binqueue-add-Some insert-def*)

lemma *normalized-insert*:

normalized xs ⇒ normalized (insert a v xs)
by (*simp add: normalized-add insert-def*)

definition

pop :: ('a::linorder, 'b) *binqueue* ⇒ (('b × 'a) *option* × ('a, 'b) *binqueue*)

where

$pop\ xs = (case\ find\ min\ xs\ of$
 $None \Rightarrow (None, xs)$
 $| Some\ t \Rightarrow (Some\ (val\ t, priority\ t), delete\ min\ xs))$

lemma *pop-empty* [simp]:

$pop\ empty = (None, empty)$
by (*simp add: pop-def empty-def*)

lemma *pop-nonempty* [simp]:

$normalized\ xs \Longrightarrow xs \neq [] \Longrightarrow find\ min\ xs = Some\ t$
 $\Longrightarrow pop\ xs = (Some\ (val\ t, priority\ t), normalize$
 $(meld\ (map\ Some\ (rev\ (children\ t)))\ (map\ (match\ (priority\ t))\ xs)))$
by (*simp add: pop-def*)

lemma *pop-code* [code]:

$pop\ xs = (case\ find\ min\ xs\ of$
 $None \Rightarrow (None, xs)$
 $| Some\ t \Rightarrow (Some\ (val\ t, priority\ t), normalize$
 $(meld\ (map\ Some\ (rev\ (children\ t)))\ (map\ (match\ (priority\ t))\ xs)))$
by (*cases find-min xs*) (*simp-all add: pop-def delete-min-def split: bintree.split*)

3 Relating Functional Binomial Queues To The Abstract Priority Queues

notation

$PQ.values\ (|(-)|)$
and $PQ.priorities\ (||(-)||)$

Naming convention: prefix *bt-* for bintrees, *bts-* for bintree lists, no prefix for binqueues.

primrec *bt-dfs* :: $((a::linorder, 'b)\ bintree \Rightarrow 'c) \Rightarrow (a, 'b)\ bintree \Rightarrow 'c\ list$
and *bts-dfs* :: $((a::linorder, 'b)\ bintree \Rightarrow 'c) \Rightarrow (a, 'b)\ bintree\ list \Rightarrow 'c\ list$

where

$bt\ dfs\ f\ (Node\ a\ v\ ts) = f\ (Node\ a\ v\ ts) \# bts\ dfs\ f\ ts$
 $| bts\ dfs\ f\ [] = []$
 $| bts\ dfs\ f\ (t \# ts) = bt\ dfs\ f\ t @ bts\ dfs\ f\ ts$

lemma *bt-dfs-simp*:

$bt\ dfs\ f\ t = f\ t \# bts\ dfs\ f\ (children\ t)$
by (*cases t simp-all*)

lemma *bts-dfs-append* [simp]:

$bts_dfs\ f\ (ts\ @\ rs) = bts_dfs\ f\ ts\ @\ bts_dfs\ f\ rs$
by $(induct\ ts)\ simp_all$

lemma *set-bts-dfs-rev*:
 $set\ (bts_dfs\ f\ (rev\ ts)) = set\ (bts_dfs\ f\ ts)$
by $(induct\ ts)\ auto$

lemma *bts-dfs-rev-distinct*:
 $distinct\ (bts_dfs\ f\ ts) \implies distinct\ (bts_dfs\ f\ (rev\ ts))$
by $(induct\ ts)\ (auto\ simp\ add:\ set_bts_dfs_rev)$

lemma *bt-dfs-comp*:
 $bt_dfs\ (f\ \circ\ g)\ t = map\ f\ (bt_dfs\ g\ t)$
 $bts_dfs\ (f\ \circ\ g)\ ts = map\ f\ (bts_dfs\ g\ ts)$
by $(induct\ t\ and\ ts\ rule:\ bt_dfs.induct\ bts_dfs.induct)\ simp_all$

lemma *bt-dfs-comp-distinct*:
 $distinct\ (bt_dfs\ (f\ \circ\ g)\ t) \implies distinct\ (bt_dfs\ g\ t)$
 $distinct\ (bts_dfs\ (f\ \circ\ g)\ ts) \implies distinct\ (bts_dfs\ g\ ts)$
by $(simp_all\ add:\ bt_dfs_comp\ distinct_map\ [of\ f])$

lemma *bt-dfs-distinct-children*:
 $distinct\ (bt_dfs\ f\ x) \implies distinct\ (bts_dfs\ f\ (children\ x))$
by $(cases\ x)\ simp$

fun *dfs* :: $(('a::linorder,\ 'b)\ bintree \Rightarrow 'c) \Rightarrow ('a,\ 'b)\ binqueue \Rightarrow 'c\ list$ **where**
 $dfs\ f\ [] = []$
 $| dfs\ f\ (None\ \#\ xs) = dfs\ f\ xs$
 $| dfs\ f\ (Some\ t\ \#\ xs) = bt_dfs\ f\ t\ @\ dfs\ f\ xs$

lemma *dfs-append*:
 $dfs\ f\ (xs\ @\ ys) = (dfs\ f\ xs)\ @\ (dfs\ f\ ys)$
by $(induct\ xs)\ simp_all$

lemma *set-dfs-rev*:
 $set\ (dfs\ f\ (rev\ xs)) = set\ (dfs\ f\ xs)$
by $(induct\ xs)\ (auto\ simp\ add:\ dfs_append)$

lemma *set-dfs-Cons*:
 $set\ (dfs\ f\ (x\ \#\ xs)) = set\ (dfs\ f\ xs) \cup set\ (dfs\ f\ [x])$
proof –
have $set\ (dfs\ f\ (x\ \#\ xs)) = set\ (dfs\ f\ (rev\ xs\ @\ [x]))$
using *set-dfs-rev* $[of\ f\ rev\ xs\ @\ [x]]$ **by** *simp*
thus *?thesis* **by** $(simp\ add:\ dfs_append\ set_dfs_rev)$
qed

lemma *dfs-comp*:

$dfs (f \circ g) xs = map f (dfs g xs)$

by (*induct xs*) (*simp-all add: bt-dfs-comp del: o-apply*)

lemma *dfs-comp-distinct*:

$distinct (dfs (f \circ g) xs) \implies distinct (dfs g xs)$

by (*simp add: dfs-comp distinct-map[of f]*)

lemma *dfs-distinct-member*:

$distinct (dfs f xs) \implies$

$Some x \in set xs \implies$

$distinct (bt-dfs f x)$

proof (*induct xs arbitrary: x*)

case (*Some r xs t*) **then show** *?case* **by** (*cases t = r*) *simp-all*

qed *simp-all*

lemma *dfs-map-Some-idem*:

$dfs f (map Some xs) = bt-dfs f xs$

by (*induct xs*) *simp-all*

primrec *alist* :: ('a, 'b) *bintree* \Rightarrow ('b \times 'a) **where**

$alist (Node a v -) = (v, a)$

lemma *alist-split-pre*:

$val t = (fst \circ alist) t$

$priority t = (snd \circ alist) t$

by (*cases t, simp*)⁺

lemma *alist-split*:

$val = fst \circ alist$

$priority = snd \circ alist$

by (*auto intro!: ext simp add: alist-split-pre*)

lemma *alist-split-set*:

$set (dfs val xs) = fst ' set (dfs alist xs)$

$set (dfs priority xs) = snd ' set (dfs alist xs)$

by (*auto simp add: dfs-comp alist-split*)

lemma *in-set-in-alist*:

assumes $Some t \in set xs$

shows $(val t, priority t) \in set (dfs alist xs)$

using *assms*

proof (*induct xs*)

case (*Some x xs*) **then show** *?case*

proof (cases Some t ∈ set xs)
 case False with Some show ?thesis by (cases t) (auto simp add: bt-dfs-simp)
qed simp
qed simp-all

abbreviation vals **where** vals ≡ dfs val
abbreviation prios **where** prios ≡ dfs priority
abbreviation elements **where** elements ≡ dfs alist

primrec
 bt-augment :: ('a::linorder, 'b) bintree ⇒ ('b, 'a) PQ.pq ⇒ ('b, 'a) PQ.pq
and
 bts-augment :: ('a::linorder, 'b) bintree list ⇒ ('b, 'a) PQ.pq ⇒ ('b, 'a) PQ.pq
where
 bt-augment (Node a v ts) q = PQ.push v a (bts-augment ts q)
 | bts-augment [] q = q
 | bts-augment (t # ts) q = bts-augment ts (bt-augment t q)

lemma bts-augment [simp]:
 bts-augment = fold bt-augment
proof (rule ext)
 fix ts :: ('a, 'b) bintree list
 show bts-augment ts = fold bt-augment ts
 by (induct ts) simp-all
qed

lemma bt-augment-Node [simp]:
 bt-augment (Node a v ts) q = PQ.push v a (fold bt-augment ts q)
 by (simp add: bts-augment)

lemma bt-augment-simp:
 bt-augment t q = PQ.push (val t) (priority t) (fold bt-augment (children t) q)
 by (cases t) (simp-all add: bts-augment)

declare bt-augment.simps [simp del] bts-augment.simps [simp del]

fun pqueue :: ('a::linorder, 'b) binqueue ⇒ ('b, 'a) PQ.pq **where**
 Empty: pqueue [] = PQ.empty
 | None: pqueue (None # xs) = pqueue xs
 | Some: pqueue (Some t # xs) = bt-augment t (pqueue xs)

lemma bt-augment-v-subset:
 set |q| ⊆ set |bt-augment t q|
 set |q| ⊆ set |bts-augment ts q|

by (*induct t and ts arbitrary: q and q rule: bt-augment.induct bts-augment.induct*)
auto

lemma *bt-augment-v-in*:

$v \in \text{set } |q| \implies v \in \text{set } |bt\text{-augment } t \ q|$
 $v \in \text{set } |q| \implies v \in \text{set } |bts\text{-augment } ts \ q|$
using *bt-augment-v-subset[of q]* **by** *auto*

lemma *bt-augment-v-union*:

$\text{set } |bt\text{-augment } t \ (bt\text{-augment } r \ q)| =$
 $\text{set } |bt\text{-augment } t \ q| \cup \text{set } |bt\text{-augment } r \ q|$
 $\text{set } |bts\text{-augment } ts \ (bt\text{-augment } r \ q)| =$
 $\text{set } |bts\text{-augment } ts \ q| \cup \text{set } |bt\text{-augment } r \ q|$

proof (*induct t and ts arbitrary: q r and q r rule: bt-augment.induct bts-augment.induct*)

case *Nil-bintree*

from *bt-augment-v-subset[of q]* **show** *?case* **by** *auto*

qed *auto*

lemma *bt-val-augment*:

shows $\text{set } (bt\text{-dfs } val \ t) \cup \text{set } |q| = \text{set } |bt\text{-augment } t \ q|$
and $\text{set } (bts\text{-dfs } val \ ts) \cup \text{set } |q| = \text{set } |bts\text{-augment } ts \ q|$

proof (*induct t and ts rule: bt-augment.induct bts-augment.induct*)

case (*Cons-bintree r rs*)

have $\text{set } |bts\text{-augment } rs \ (bt\text{-augment } r \ q)| =$
 $\text{set } |bts\text{-augment } rs \ q| \cup \text{set } |bt\text{-augment } r \ q|$
by (*simp only: bt-augment-v-union*)

with *bt-augment-v-subset[of q]*

have $\text{set } |bts\text{-augment } rs \ (bt\text{-augment } r \ q)| =$
 $\text{set } |bts\text{-augment } rs \ q| \cup \text{set } |bt\text{-augment } r \ q| \cup \text{set } |q|$
by *auto*

with *Cons-bintree* **show** *?case* **by** *auto*

qed *auto*

lemma *vals-pqueue*:

$\text{set } (vals \ xs) = \text{set } |pqueue \ xs|$
by (*induct xs*) (*simp-all add: bt-val-augment*)

lemma *bt-augment-v-push*:

$\text{set } |bt\text{-augment } t \ (PQ.\text{push } v \ a \ q)| = \text{set } |bt\text{-augment } t \ q| \cup \{v\}$
 $\text{set } |bts\text{-augment } ts \ (PQ.\text{push } v \ a \ q)| = \text{set } |bts\text{-augment } ts \ q| \cup \{v\}$
using *bt-val-augment[where q = PQ.push v a q]* **by** (*simp-all add: bt-val-augment*)

lemma *bt-augment-v-push-commute*:

$\text{set } |bt\text{-augment } t \ (PQ.\text{push } v \ a \ q)| = \text{set } |PQ.\text{push } v \ a \ (bt\text{-augment } t \ q)|$

$set \ |bts\text{-augment } ts \ (PQ.push \ v \ a \ q)| = set \ |PQ.push \ v \ a \ (bts\text{-augment } ts \ q)|$
by (*simp-all add: bt-augment-v-push del: bts-augment*)

lemma *bts-augment-v-union*:

$set \ |bt\text{-augment } t \ (bts\text{-augment } rs \ q)| =$
 $set \ |bt\text{-augment } t \ q| \cup set \ |bts\text{-augment } rs \ q|$
 $set \ |bts\text{-augment } ts \ (bts\text{-augment } rs \ q)| =$
 $set \ |bts\text{-augment } ts \ q| \cup set \ |bts\text{-augment } rs \ q|$

proof (*induct t and ts arbitrary: q rs and q rs rule: bt-augment.induct bts-augment.induct*)

case *Nil-bintree*

from *bt-augment-v-subset[of q]* **show** *?case by auto*

next

case (*Cons-bintree x xs*)

let $?L = set \ |bts\text{-augment } xs \ (bt\text{-augment } x \ (bts\text{-augment } rs \ q))|$

from *bt-augment-v-union*

have $*$: $\bigwedge q. set \ |bts\text{-augment } xs \ (bt\text{-augment } x \ q)| =$
 $set \ |bts\text{-augment } xs \ q| \cup set \ |bt\text{-augment } x \ q|$ **by** *simp*

with *Cons-bintree*

have $?L =$

$set \ |bts\text{-augment } xs \ q| \cup set \ |bts\text{-augment } rs \ q| \cup set \ |bt\text{-augment } x \ q|$
by *auto*

with $*$ **show** *?case by auto*

qed *simp*

lemma *bt-augment-v-commute*:

$set \ |bt\text{-augment } t \ (bt\text{-augment } r \ q)| = set \ |bt\text{-augment } r \ (bt\text{-augment } t \ q)|$
 $set \ |bt\text{-augment } t \ (bts\text{-augment } rs \ q)| = set \ |bts\text{-augment } rs \ (bt\text{-augment } t \ q)|$
 $set \ |bts\text{-augment } ts \ (bts\text{-augment } rs \ q)| =$
 $set \ |bts\text{-augment } rs \ (bts\text{-augment } ts \ q)|$

unfolding *bts-augment-v-union bt-augment-v-union by auto*

lemma *bt-augment-v-merge*:

$set \ |bt\text{-augment } (merge \ t \ r) \ q| = set \ |bt\text{-augment } t \ (bt\text{-augment } r \ q)|$
by (*simp add: bt-augment-simp [symmetric] bt-augment-v-push*
bt-augment-v-commute merge-def)

lemma *vals-merge [simp]*:

$set \ (bt\text{-dfs } val \ (merge \ t \ r)) = set \ (bt\text{-dfs } val \ t) \cup set \ (bt\text{-dfs } val \ r)$
by (*auto simp add: bt-dfs-simp merge-def*)

lemma *vals-merge-distinct*:

$distinct \ (bt\text{-dfs } val \ t) \implies distinct \ (bt\text{-dfs } val \ r) \implies$

$set (bt\text{-}dfs\ val\ t) \cap set (bt\text{-}dfs\ val\ r) = \{\} \implies$
 $distinct (bt\text{-}dfs\ val\ (merge\ t\ r))$
by (*auto simp add: bt-dfs-simp merge-def*)

lemma *vals-add-Cons*:
 $set (vals (add\ x\ xs)) = set (vals (x\ \#\ xs))$
proof (*cases x*)
case (*Some t*) **then show** *?thesis*
by (*induct xs arbitrary: x t auto*)
qed *simp*

lemma *vals-add-distinct*:
assumes $distinct (vals\ xs)$
and $distinct (dfs\ val\ [x])$
and $set (vals\ xs) \cap set (dfs\ val\ [x]) = \{\}$
shows $distinct (vals (add\ x\ xs))$
using *assms*
proof (*cases x*)
case (*Some t*) **with** *assms show* *?thesis*
proof (*induct xs arbitrary: x t*)
case (*Some r xs*)
then have $set (bt\text{-}dfs\ val\ t) \cap set (bt\text{-}dfs\ val\ r) = \{\}$ **by** *auto*
with *Some* **have** $distinct (bt\text{-}dfs\ val (merge\ t\ r))$ **by** (*simp add: vals-merge-distinct*)
moreover
with *Some* **have** $set (vals\ xs) \cap set (bt\text{-}dfs\ val (merge\ t\ r)) = \{\}$ **by** *auto*

moreover note *Some*
ultimately show *?case* **by** *simp*
qed *auto*
qed *simp*

lemma *vals-insert [simp]*:
 $set (vals (insert\ a\ v\ xs)) = set (vals\ xs) \cup \{v\}$
by (*simp add: insert-def vals-add-Cons*)

lemma *insert-v-push*:
 $set (vals (insert\ a\ v\ xs)) = set |PQ.push\ v\ a\ (pqueue\ xs)|$
by (*simp add: vals-pqueue[symmetric]*)

lemma *vals-meld*:
 $set (dfs\ val (meld\ xs\ ys)) = set (dfs\ val\ xs) \cup set (dfs\ val\ ys)$
proof (*induct xs ys rule: meld.induct*)
case ($\exists\ xs\ y\ ys$) **then show** *?case*
using *set-dfs-Cons[of val y meld xs ys]* **using** *set-dfs-Cons[of val y ys]* **by** *auto*
next

case (4 x xs ys) **then show** ?case
using set-dfs-Cons[of val x meld xs ys] **using** set-dfs-Cons[of val x xs] **by** auto
next
case (5 x xs y ys) **then show** ?case **by** (auto simp add: vals-add-Cons)
qed simp-all

lemma vals-meld-distinct:

$distinct (dfs\ val\ xs) \implies distinct (dfs\ val\ ys) \implies$
 $set (dfs\ val\ xs) \cap set (dfs\ val\ ys) = \{\}$ \implies
 $distinct (dfs\ val\ (meld\ xs\ ys))$

proof (induct xs ys rule: meld.induct)

case (3 xs y ys) **then show** ?case

proof (cases y)

case None **with** 3 **show** ?thesis **by** simp

next

case (Some t)

from 3 **have** A : $set (vals\ xs) \cap set (vals\ ys) = \{\}$

using set-dfs-Cons[of val y ys] **by** auto

moreover

from Some 3 **have** $set (bt\ dfs\ val\ t) \cap set (vals\ xs) = \{\}$ **by** auto

moreover

from Some 3 **have** $set (bt\ dfs\ val\ t) \cap set (vals\ ys) = \{\}$ **by** simp

ultimately have $set (bt\ dfs\ val\ t) \cap set (vals (meld\ xs\ ys)) = \{\}$

by (auto simp add: vals-meld)

with 3 Some **show** ?thesis **by** auto

qed

next

case (4 x xs ys) **then show** ?case

proof (cases x)

case None **with** 4 **show** ?thesis **by** simp

next

case (Some t)

from 4 **have** $set (vals\ xs) \cap set (vals\ ys) = \{\}$

using set-dfs-Cons[of val x xs] **by** auto

moreover

from Some 4 **have** $set (bt\ dfs\ val\ t) \cap set (vals\ xs) = \{\}$ **by** simp

moreover

from Some 4 **have** $set (bt\ dfs\ val\ t) \cap set (vals\ ys) = \{\}$ **by** auto

ultimately have $set (bt\ dfs\ val\ t) \cap set (vals (meld\ xs\ ys)) = \{\}$

```

    by (auto simp add: vals-meld)
  with 4 Some show ?thesis by auto
qed
next
case (5 x xs y ys) then
have set (vals xs) ∩ set (vals ys) = {} by (auto simp add: set-dfs-Cons)
with 5 have distinct (vals (meld xs ys)) by simp

moreover
from 5 have set (bt-dfs val x) ∩ set (bt-dfs val y) = {} by auto
with 5 have distinct (bt-dfs val (merge x y))
  by (simp add: vals-merge-distinct)

moreover
from 5 have set (vals (meld xs ys)) ∩ set (bt-dfs val (merge x y)) = {}
  by (auto simp add: vals-meld)

ultimately show ?case by (simp add: vals-add-distinct)
qed simp-all

lemma bt-augment-alist-subset:
  set (PQ.alist-of q) ⊆ set (PQ.alist-of (bt-augment t q))
  set (PQ.alist-of q) ⊆ set (PQ.alist-of (bts-augment ts q))
proof (induct t and ts arbitrary: q and q rule: bt-augment.induct bts-augment.induct)
  case (Node a v rs)
  show ?case using Node[of q] by (auto simp add: bt-augment-simp set-insort-key)
qed auto

lemma bt-augment-alist-in:
  (v,a) ∈ set (PQ.alist-of q) ⇒ (v,a) ∈ set (PQ.alist-of (bt-augment t q))
  (v,a) ∈ set (PQ.alist-of q) ⇒ (v,a) ∈ set (PQ.alist-of (bts-augment ts q))
  using bt-augment-alist-subset[of q] by auto

lemma bt-augment-alist-union:
  distinct (bts-dfs val (r # [t])) ⇒
  set (bts-dfs val (r # [t])) ∩ set |q| = {} ⇒
  set (PQ.alist-of (bt-augment t (bt-augment r q))) =
  set (PQ.alist-of (bt-augment t q)) ∪ set (PQ.alist-of (bt-augment r q))

  distinct (bts-dfs val (r # ts)) ⇒
  set (bts-dfs val (r # ts)) ∩ set |q| = {} ⇒
  set (PQ.alist-of (bts-augment ts (bt-augment r q))) =
  set (PQ.alist-of (bts-augment ts q)) ∪ set (PQ.alist-of (bt-augment r q))
proof (induct t and ts arbitrary: q r and q r rule: bt-augment.induct bts-augment.induct)
  case Nil-bintree

```

from *bt-augment-alist-subset*[of *q*] **show** ?*case* **by** *auto*
next
case (*Node a v rs*) **then**
have
 $set (PQ.alist-of (bts-augment rs (bt-augment r q))) =$
 $set (PQ.alist-of (bts-augment rs q)) \cup set (PQ.alist-of (bt-augment r q))$
by *simp*

moreover
from *Node.prem*s **have** *: $v \notin set |bts-augment rs q| \cup set |bt-augment r q|$
unfolding *bt-val-augment*[*symmetric*] **by** *simp*
hence $v \notin set |bts-augment rs (bt-augment r q)|$ **by** (*unfold bt-augment-v-union*)

moreover
from * **have** $v \notin set |bts-augment rs q|$ **by** *simp*

ultimately show ?*case* **by** (*simp add: set-insort-key*)
next
case (*Cons-bintree x xs*) **then**
have — *FIXME*: ugly... and slow
 $distinct (bts-dfs val (x \# xs))$ **and**
 $distinct (bts-dfs val (r \# xs))$ **and**
 $distinct (bts-dfs val [r,x])$ **and**
 $set (bts-dfs val (x \# xs)) \cap set |bt-augment r q| = \{\}$ **and**
 $set (bts-dfs val (x \# xs)) \cap set |q| = \{\}$ **and**
 $set (bts-dfs val [r, x]) \cap set |q| = \{\}$ **and**
 $set (bts-dfs val (r \# xs)) \cap set |q| = \{\}$
unfolding *bt-val-augment*[*symmetric*] **by** *auto*
with *Cons-bintree.hyps* **show** ?*case* **by** *auto*
qed

lemma *bt-alist-augment*:
 $distinct (bt-dfs val t) \implies$
 $set (bt-dfs val t) \cap set |q| = \{\} \implies$
 $set (bt-dfs alist t) \cup set (PQ.alist-of q) = set (PQ.alist-of (bt-augment t q))$

 $distinct (bts-dfs val ts) \implies$
 $set (bts-dfs val ts) \cap set |q| = \{\} \implies$
 $set (bts-dfs alist ts) \cup set (PQ.alist-of q) =$
 $set (PQ.alist-of (bts-augment ts q))$
proof (*induct t and ts rule: bt-augment.induct bts-augment.induct*)
case *Nil-bintree* **then show** ?*case* **by** *simp*
next
case (*Node a v rs*)
hence $v \notin set |bts-augment rs q|$

unfolding *bt-val-augment*[*symmetric*] **by** *simp*
with *Node* **show** *?case* **by** (*simp* *add: set-insort-key*)
next
case (*Cons-bintree* *r rs*) **then**
have *set (PQ.alist-of (bts-augment (r # rs) q)) =*
set (PQ.alist-of (bts-augment rs q)) ∪ set (PQ.alist-of (bt-augment r q))
using *bt-augment-alist-union* **by** *simp*
with *Cons-bintree* *bt-augment-alist-subset* **show** *?case* **by** *auto*
qed

lemma *alist-pqueue*:
distinct (vals xs) ⇒ set (dfs alist xs) = set (PQ.alist-of (pqueue xs))
by (*induct* *xs*) (*simp-all* *add: vals-pqueue bt-alist-augment*)

lemma *alist-pqueue-priority*:
distinct (vals xs) ⇒ (v, a) ∈ set (dfs alist xs)
 $\implies PQ.priority (pqueue xs) v = Some\ a$
by (*simp* *add: alist-pqueue PQ.priority-def*)

lemma *prios-pqueue*:
distinct (vals xs) ⇒ set (prios xs) = set ||pqueue xs||
by (*auto* *simp* *add: alist-pqueue priorities-set alist-split-set*)

lemma *alist-merge* [*simp*]:
distinct (bt-dfs val t) ⇒ distinct (bt-dfs val r) ⇒
set (bt-dfs val t) ∩ set (bt-dfs val r) = {} ⇒
set (bt-dfs alist (merge t r)) = set (bt-dfs alist t) ∪ set (bt-dfs alist r)
by (*auto* *simp* *add: bt-dfs-simp merge-def alist-split*)

lemma *alist-add-Cons*:
assumes *distinct (vals (x#xs))*
shows *set (dfs alist (add x xs)) = set (dfs alist (x # xs))*
using *assms* **proof** (*induct* *xs* *arbitrary: x*)
case *Empty* **then** **show** *?case* **by** (*cases* *x*) *simp-all*
next
case *None* **then** **show** *?case* **by** (*cases* *x*) *simp-all*
next
case (*Some* *y ys*) **then**
show *?case*
proof (*cases* *x*)
case (*Some* *t*)
note *prem = Some.prem* *Some*

from *prem* **have** *distinct (bt-dfs val (merge t y))*
by (*auto* *simp* *add: bt-dfs-simp merge-def*)

with *prem* **have** $\text{distinct (vals (Some (merge t y) \# ys))}$ **by** *auto*
with *prem Some.hyps*
have $\text{set (dfs alist (add (Some (merge t y)) ys)) =}$
 $\text{set (dfs alist (Some (merge t y) \# ys))}$ **by** *simp*

moreover
from *prem* **have** $\text{set (bt-dfs val t) \cap set (bt-dfs val y) = \{\}}$ **by** *auto*
with *prem*
have $\text{set (bt-dfs alist (merge t y)) =}$
 $\text{set (bt-dfs alist t) \cup set (bt-dfs alist y)}$
by *simp*

moreover note *prem* **and** *Un-assoc*

ultimately
show *?thesis* **by** *simp*
qed *simp*
qed

lemma *alist-insert [simp]*:
 $\text{distinct (vals xs)} \implies$
 $v \notin \text{set (vals xs)} \implies$
 $\text{set (dfs alist (insert a v xs)) = set (dfs alist xs) \cup \{(v,a)\}}$
by (*simp add: insert-def alist-add-Cons*)

lemma *insert-push*:
 $\text{distinct (vals xs)} \implies$
 $v \notin \text{set (vals xs)} \implies$
 $\text{set (dfs alist (insert a v xs)) = set (PQ.alist-of (PQ.push v a (pqueue xs)))}$
by (*simp add: alist-pqueue vals-pqueue set-insort-key*)

lemma *insert-p-push*:
assumes $\text{distinct (vals xs)}$
and $v \notin \text{set (vals xs)}$
shows $\text{set (prio (insert a v xs)) = set \|\text{PQ.push v a (pqueue xs)}\|}$
proof –
from *assms*
have $\text{set (dfs alist (insert a v xs)) =}$
 $\text{set (PQ.alist-of (PQ.push v a (pqueue xs)))}$
by (*rule insert-push*)
thus *?thesis* **by** (*simp add: alist-split-set priorities-set*)
qed

lemma *empty-empty*:
 $\text{normalized xs} \implies \text{xs = empty} \iff \text{PQ.is-empty (pqueue xs)}$

```

proof (rule iffI)
  assume  $xs = []$  then show  $PQ.is-empty (pqueue xs)$  by simp
next
  assume  $N$ : normalized  $xs$  and  $E$ :  $PQ.is-empty (pqueue xs)$ 
  show  $xs = []$ 
  proof (rule ccontr)
    assume  $xs \neq []$ 
    with  $N$  have  $set (vals xs) \neq \{\}$ 
      by (induct  $xs$ ) (simp-all add: bt-dfs-simp dfs-append)
    hence  $set |pqueue xs| \neq \{\}$  by (simp add: vals-pqueue)

    moreover
    from  $E$  have  $set |pqueue xs| = \{\}$  by (simp add: is-empty-empty)

    ultimately show  $False$  by simp
  qed
qed

```

```

lemma bt-dfs-Min-priority:
  assumes  $is-heap t$ 
  shows  $priority t = Min (set (bt-dfs priority t))$ 
using  $assms$ 
proof (induct  $priority t$  children  $t$  arbitrary:  $t$ )
  case  $is-heap-list-Nil$  then show ?case by (simp add: bt-dfs-simp)
next
  case ( $is-heap-list-Cons rs r t$ ) note  $cons = this$ 
  let  $?M = Min (set (bt-dfs priority t))$ 

  obtain  $t'$  where  $t' = Node (priority t) (val t) rs$  by auto
  hence  $ot: rs = children t' priority t' = priority t$  by simp-all
  with  $is-heap-list-Cons$  have  $priority t = Min (set (bt-dfs priority t'))$ 
    by simp
  with  $ot$ 
    have  $priority t = Min (Set.insert (priority t) (set (bts-dfs priority rs)))$ 
    by (simp add: bt-dfs-simp)

  moreover
  from  $cons$  have  $priority r = Min (set (bt-dfs priority r))$  by simp

  moreover
  from  $cons$  have  $children t = r \# rs$  by simp
  then have  $bts-dfs priority (children t) =$ 
    ( $bt-dfs priority r$ ) @ ( $bts-dfs priority rs$ ) by simp
  hence  $bt-dfs priority t =$ 
     $priority t \# (bt-dfs priority r @ bts-dfs priority rs)$ 

```

by (*simp add: bt-dfs-simp*)
hence $A: ?M = \text{Min}$
 $(\text{Set.insert } (\text{priority } t) (\text{set } (\text{bt-dfs priority } r) \cup \text{set } (\text{bts-dfs priority } rs)))$
by *simp*

have $\text{Set.insert } (\text{priority } t) (\text{set } (\text{bt-dfs priority } r) \cup \text{set } (\text{bts-dfs priority } rs)) =$
 $\text{Set.insert } (\text{priority } t) (\text{set } (\text{bts-dfs priority } rs) \cup \text{set } (\text{bt-dfs priority } r))$
by *auto*

with A **have** $?M = \text{Min}$
 $(\text{Set.insert } (\text{priority } t) (\text{set } (\text{bts-dfs priority } rs) \cup \text{set } (\text{bt-dfs priority } r)))$
by *simp*

with *Min-Un*
 $[\text{of } \text{Set.insert } (\text{priority } t) (\text{set } (\text{bts-dfs priority } rs) \cup \text{set } (\text{bt-dfs priority } r))]$
have $?M =$
 $\text{ord-class.min } (\text{Min } (\text{Set.insert } (\text{priority } t) (\text{set } (\text{bts-dfs priority } rs))))$
 $(\text{Min } (\text{set } (\text{bt-dfs priority } r)))$
by (*auto simp add: bt-dfs-simp*)

ultimately
have $?M = \text{ord-class.min } (\text{priority } t) (\text{priority } r)$ **by** *simp*

with $\langle \text{priority } t \leq \text{priority } r \rangle$ **show** $?case$ **by** (*auto simp add: ord-class.min-def*)
qed

lemma *is-binnacle-min-Min-prios*:
assumes *is-binnacle l xs*
and *normalized xs*
and $xs \neq []$
shows $\text{min } xs = \text{Some } (\text{Min } (\text{set } (\text{prios } xs)))$
using *assms*

proof (*induct xs*)
case (*Some l xs x*) **then show** $?case$
proof (*cases xs $\neq []$*)
case *False* **with** *Some* **show** $?thesis$
using *bt-dfs-Min-priority[of x]* **by** (*simp add: min-single*)
next
case *True* **note** $T = \text{this Some}$

from T **have** *normalized xs* **by** *simp*
with $\langle xs \neq [] \rangle$ **have** $\text{prios } xs \neq []$ **by** (*induct xs*) (*simp-all add: bt-dfs-simp*)
with T **show** $?thesis$
using *Min-Un[of set (bt-dfs priority x) set (prios xs)]*
using *bt-dfs-Min-priority[of x]*

by (auto simp add: bt-dfs-simp ord-class.min-def)
qed
qed simp-all

lemma min-p-min:
assumes *is-binqueue l xs*
and $xs \neq []$
and *normalized xs*
and *distinct (vals xs)*
and *distinct (prios xs)*
shows $min\ xs = PQ.priority\ (pqueue\ xs)\ (PQ.min\ (pqueue\ xs))$
proof –
from $\langle xs \neq [] \rangle$ $\langle normalized\ xs \rangle$ **have** $\neg PQ.is-empty\ (pqueue\ xs)$
by (simp add: empty-empty)
moreover
from *assms* **have** $min\ xs = Some\ (Min\ (set\ (prios\ xs)))$
by (simp add: is-binqueue-min-Min-prios)
with $\langle distinct\ (vals\ xs) \rangle$ **have** $min\ xs = Some\ (Min\ (set\ \|pqueue\ xs\|))$
by (simp add: prios-pqueue)
ultimately show *?thesis*
by (simp add: priority-Min-priorities [where $q = pqueue\ xs$])
qed

lemma find-min-p-min:
assumes *is-binqueue l xs*
and $xs \neq []$
and *normalized xs*
and *distinct (vals xs)*
and *distinct (prios xs)*
shows $priority\ (the\ (find-min\ xs)) =$
 $the\ (PQ.priority\ (pqueue\ xs)\ (PQ.min\ (pqueue\ xs)))$
proof –
from *assms* **have** $min\ xs \neq None$ **by** (simp add: normalized-min-not-None)
from *assms* **have** $min\ xs = PQ.priority\ (pqueue\ xs)\ (PQ.min\ (pqueue\ xs))$
by (simp add: min-p-min)
with $\langle min\ xs \neq None \rangle$ **show** *?thesis* **by** (auto simp add: min-eq-find-min-Some)
qed

lemma find-min-v-min:
assumes *is-binqueue l xs*
and $xs \neq []$
and *normalized xs*
and *distinct (vals xs)*

and *distinct* (*prios xs*)
shows *val* (*the* (*find-min xs*)) = *PQ.min* (*pqueue xs*)
proof –
from *assms* **have** *min xs* \neq *None* **by** (*simp add: normalized-min-not-None*)
then obtain *a* **where** *oa: Some a = min xs* **by** *auto*
then obtain *t* **where** *ot: find-min xs = Some t priority t = a*
using *min-eq-find-min-Some [of xs a]* **by** *auto*

hence $*$: (*val t, a*) \in *set* (*dfs alist xs*)
by (*auto simp add: find-min-exist in-set-in-alist*)

have *PQ.min* (*pqueue xs*) = *val t*
proof (*rule ccontr*)
assume *A: PQ.min* (*pqueue xs*) \neq *val t*
then obtain *t'* **where** *ot': PQ.min* (*pqueue xs*) = *t'* **by** *simp*
with *A* **have** *NE: val t* \neq *t'* **by** *simp*

from *ot' oa assms* **have** (*t', a*) \in *set* (*dfs alist xs*)
by (*simp add: alist-pqueue PQ.priority-def min-p-min*)

with $*$ *NE* **have** \neg *distinct* (*prios xs*)
unfolding *alist-split*(2)
unfolding *dfs-comp*
by (*induct* (*dfs alist xs*)) (*auto simp add: rev-image-eqI*)
with \langle *distinct* (*prios xs*) \rangle **show** *False* **by** *simp*
qed
with *ot* **show** *?thesis* **by** *auto*
qed

lemma *alist-normalize-idem*:
dfs alist (*normalize xs*) = *dfs alist xs*
unfolding *normalize-def*
proof (*induct xs rule: rev-induct*)
case (*snoc x xs*) **then show** *?case* **by** (*cases x*) (*simp-all add: dfs-append*)
qed *simp*

lemma *dfs-match-not-in*:
 $(\forall t. \text{Some } t \in \text{set } xs \longrightarrow \text{priority } t \neq a) \implies$
 $\text{set } (\text{dfs } f \text{ (map (match } a \text{) } xs)) = \text{set } (\text{dfs } f \text{ } xs)$
by (*induct xs*) *simp-all*

lemma *dfs-match-subset*:
 $\text{set } (\text{dfs } f \text{ (map (match } a \text{) } xs)) \subseteq \text{set } (\text{dfs } f \text{ } xs)$
proof (*induct xs rule: list.induct*)
case (*Cons x xs*) **then show** *?case* **by** (*cases x*) *auto*

qed *simp*

lemma *dfs-match-distinct*:

$distinct (dfs f xs) \implies distinct (dfs f (map (match a) xs))$

proof (*induct xs rule: list.induct*)

case (*Cons x xs*) **then show** *?case*

using *dfs-match-subset[of f a xs]*

by (*cases x, auto*)

qed *simp*

lemma *dfs-match*:

$distinct (prios xs) \implies$

$distinct (dfs f xs) \implies$

$Some t \in set xs \implies$

$priority t = a \implies$

$set (dfs f (map (match a) xs)) = set (dfs f xs) - set (bt-dfs f t)$

proof (*induct xs arbitrary: t*)

case (*Some r xs t*) **then show** *?case*

proof (*cases t = r*)

case *True*

from *Some* **have** $priority r \notin set (prios xs)$ **by** (*auto simp add: bt-dfs-simp*)

with *Some True* **have** $a \notin set (prios xs)$ **by** *simp*

hence $\forall s. Some s \in set xs \longrightarrow priority s \neq a$

by (*induct xs*) (*auto simp add: bt-dfs-simp*)

hence $set (dfs f (map (match a) xs)) = set (dfs f xs)$

by (*simp add: dfs-match-not-in*)

with *True Some* **show** *?thesis* **by** *auto*

next

case *False*

with *Some.prem*s **have** $Some t \in set xs$ **by** *simp*

with $\langle priority t = a \rangle$ **have** $a \in set (prios xs)$

proof (*induct xs*)

case (*Some x xs*) **then show** *?case*

by (*cases t = x*) (*simp-all add: bt-dfs-simp*)

qed *simp-all*

with *False Some* **have** $priority r \neq a$ **by** (*auto simp add: bt-dfs-simp*)

moreover

from *Some False*

have $set (dfs f (map (match a) xs)) = set (dfs f xs) - set (bt-dfs f t)$

by *simp*

moreover

from *Some.prem*s *False* **have** $set (bt-dfs f t) \cap set (bt-dfs f r) = \{\}$

by (*induct xs*) *auto*

hence $\text{set } (bt\text{-dfs } f r) - \text{set } (bt\text{-dfs } f t) = \text{set } (bt\text{-dfs } f r)$ **by** *auto*

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

qed

qed *simp-all*

lemma *alist-meld*:

$\text{distinct } (dfs \text{ val } xs) \implies \text{distinct } (dfs \text{ val } ys) \implies$

$\text{set } (dfs \text{ val } xs) \cap \text{set } (dfs \text{ val } ys) = \{\}$ \implies

$\text{set } (dfs \text{ alist } (\text{meld } xs \ ys)) = \text{set } (dfs \text{ alist } xs) \cup \text{set } (dfs \text{ alist } ys)$

proof (*induct xs ys rule: meld.induct*)

case ($\exists \ x \ y \ ys$)

have $\text{set } (dfs \text{ alist } (y \# \text{meld } xs \ ys)) =$

$\text{set } (dfs \text{ alist } xs) \cup \text{set } (dfs \text{ alist } (y \# \ ys))$

proof –

note $assms = 3$

from $assms$ **have** $\text{set } (vals \ xs) \cap \text{set } (vals \ ys) = \{\}$

using *set-dfs-Cons[of val y ys]* **by** *auto*

moreover

from $assms$ **have** $\text{distinct } (vals \ ys)$ **by** (*cases y*) *simp-all*

moreover

from $assms$ **have** $\text{distinct } (vals \ xs)$ **by** *simp*

moreover note $assms$

ultimately have $\text{set } (dfs \text{ alist } (\text{meld } xs \ ys)) =$

$\text{set } (dfs \text{ alist } xs) \cup \text{set } (dfs \text{ alist } ys)$ **by** *simp*

hence $\text{set } (dfs \text{ alist } (y \# \text{meld } xs \ ys)) =$

$\text{set } (dfs \text{ alist } [y]) \cup \text{set } (dfs \text{ alist } xs) \cup \text{set } (dfs \text{ alist } ys)$

using *set-dfs-Cons[of alist y meld xs ys]* **by** *auto*

then show *?thesis* **using** *set-dfs-Cons[of alist y ys]* **by** *auto*

qed

thus *?case* **by** *simp*

next

case ($4 \ x \ xs \ ys$)

have $\text{set } (dfs \text{ alist } (x \# \text{meld } xs \ ys)) =$

$\text{set } (dfs \text{ alist } (x \# \ xs)) \cup \text{set } (dfs \text{ alist } ys)$

proof –

note $assms = 4$

from $assms$ **have** $\text{set } (vals \ xs) \cap \text{set } (vals \ ys) = \{\}$

using *set-dfs-Cons[of val x xs]* **by** *auto*

moreover
from *assms* **have** *distinct (vals xs)* **by** (*cases x*) *simp-all*

moreover
from *assms* **have** *distinct (vals ys)* **by** *simp*

moreover note *assms*
ultimately have *set (dfs alist (meld xs ys)) = set (dfs alist xs) ∪ set (dfs alist ys)* **by** *simp*

hence *set (dfs alist (x # meld xs ys)) = set (dfs alist [x]) ∪ set (dfs alist xs) ∪ set (dfs alist ys)*
using *set-dfs-Cons[of alist x meld xs ys]* **by** *auto*

then show *?thesis* **using** *set-dfs-Cons[of alist x xs]* **by** *auto*
qed

thus *?case* **by** *simp*

next
case (5 *x xs y ys*)
have *set (dfs alist (add (Some (merge x y)) (meld xs ys))) = set (bt-dfs alist x) ∪ set (dfs alist xs) ∪ set (bt-dfs alist y) ∪ set (dfs alist ys)*
proof –
note *assms = 5*

from *assms* **have** *distinct (bt-dfs val x) distinct (bt-dfs val y)* **by** *simp-all*
moreover from *assms* **have** *xyint*:
set (bt-dfs val x) ∩ set (bt-dfs val y) = {} **by** (*auto simp add: set-dfs-Cons*)
ultimately have *: *set (dfs alist [Some (merge x y)]) = set (bt-dfs alist x) ∪ set (bt-dfs alist y)* **by** *auto*

moreover
from *assms*
have **: *set (dfs alist (meld xs ys)) = set (dfs alist xs) ∪ set (dfs alist ys)*
by (*auto simp add: set-dfs-Cons*)

moreover
from *assms* **have** *distinct (vals (Some (merge x y) # meld xs ys))*
proof –
from *assms xyint* **have** *distinct (bt-dfs val (merge x y))*
by (*simp add: vals-merge-distinct*)

moreover
from *assms* **have**
distinct (vals xs)

and *distinct* (*vals ys*)
and $\text{set } (\text{vals } xs) \cap \text{set } (\text{vals } ys) = \{\}$
by (*auto simp add: set-dfs-Cons*)
hence *distinct* (*vals (meld xs ys)*) **by** (*rule vals-meld-distinct*)

moreover
from *assms*
have $\text{set } (\text{bt-dfs val } (\text{merge } x \ y)) \cap \text{set } (\text{vals } (\text{meld } xs \ ys)) = \{\}$
by (*auto simp add: vals-meld*)

ultimately show *?thesis* **by** *simp*
qed

ultimately show *?thesis* **by** (*auto simp add: alist-add-Cons*)
qed
thus *?case* **by** *auto*
qed *simp-all*

lemma *alist-delete-min:*

assumes *distinct* (*vals xs*)
and *distinct* (*prios xs*)
and *find-min xs = Some (Node a v ts)*
shows $\text{set } (\text{dfs alist } (\text{delete-min } xs)) = \text{set } (\text{dfs alist } xs) - \{(v, a)\}$

proof –

from $\langle \text{distinct } (\text{vals } xs) \rangle$ **have** *d: distinct* (*dfs alist xs*)
using *dfs-comp-distinct*[*of fst alist xs*]
by (*simp only: alist-split*)

from *assms* **have** *IN: Some (Node a v ts) ∈ set xs*
by (*simp add: find-min-exist*)
hence *sub: set (bts-dfs alist ts) ⊆ set (dfs alist xs)*
by (*induct xs*) (*auto simp add: bt-dfs-simp*)

from *d IN* **have** $(v, a) \notin \text{set } (\text{bts-dfs alist } ts)$
using *dfs-distinct-member*[*of alist xs Node a v ts*] **by** *simp*
with *sub* **have** $\text{set } (\text{bts-dfs alist } ts) \subseteq \text{set } (\text{dfs alist } xs) - \{(v, a)\}$ **by** *blast*
hence *nu: set (bts-dfs alist ts) ∪ (set (dfs alist xs) - {(v, a)}) =*
 $\text{set } (\text{dfs alist } xs) - \{(v, a)\}$ **by** *auto*

from *assms* **have** *distinct* (*vals (map (match a) xs)*)
by (*simp add: dfs-match-distinct*)

moreover
from *IN assms* **have** *distinct* (*bts-dfs val ts*)
using *dfs-distinct-member*[*of val xs Node a v ts*]

by (simp add: bt-dfs-distinct-children)
 hence distinct (vals (map Some (rev ts)))
 by (simp add: bts-dfs-rev-distinct dfs-map-Some-idem)

moreover

from assms IN have set (dfs val (map (match a) xs)) =
 set (dfs val xs) - set (bt-dfs val (Node a v ts))
 by (simp add: dfs-match)
 hence set (vals (map (match a) xs)) \cap set (vals (map Some (rev ts))) = {}
 by (auto simp add: dfs-map-Some-idem set-bts-dfs-rev)

ultimately

have set (dfs alist (meld (map Some (rev ts)) (map (match a) xs))) =
 set (dfs alist (map Some (rev ts))) \cup set (dfs alist (map (match a) xs))
 using alist-meld by auto

with assms d IN nu show ?thesis

by (simp add: delete-min-def alist-normalize-idem set-bts-dfs-rev dfs-map-Some-idem
 dfs-match Diff-insert2 [of set (dfs alist xs) (v,a) set (bts-dfs alist ts)])

qed

lemma alist-remove-min:

assumes is-binqueue l xs
 and distinct (vals xs)
 and distinct (prios xs)
 and normalized xs
 and xs \neq []
 shows set (dfs alist (delete-min xs)) =
 set (PQ.alist-of (PQ.remove-min (pqueue xs)))

proof -

from assms obtain t where ot: find-min xs = Some t
 using normalized-find-min-exists by auto

with assms show ?thesis

proof (cases t)

case (Node a v ys)

from assms have \neg PQ.is-empty (pqueue xs) by (simp add: empty-empty)

hence set (PQ.alist-of (PQ.remove-min (pqueue xs))) =

set (PQ.alist-of (pqueue xs) - {(PQ.min (pqueue xs),
 the (PQ.priority (pqueue xs) (PQ.min (pqueue xs)))})

by (simp add: set-alist-of-remove-min[of pqueue xs] del: alist-of-remove-min)

moreover

from assms ot Node

have set (dfs alist (delete-min xs)) = set (dfs alist xs) - {(v, a)}

using alist-delete-min[of xs] by simp

moreover
from *Node* **ot** **have** *priority (the (find-min xs)) = a* **by** *simp*
with *assms* **have** *a = the (PQ.priority (pqueue xs) (PQ.min (pqueue xs)))*
by (*simp add: find-min-p-min*)

moreover
from *Node* **ot** **have** *val (the (find-min xs)) = v* **by** *simp*
with *assms* **have** *v = PQ.min (pqueue xs)* **by** (*simp add: find-min-v-min*)

moreover **note** *⟨distinct (vals xs)⟩*
ultimately show *?thesis* **by** (*simp add: alist-pqueue*)

qed
qed

no-notation
PQ.values ($\|(-)\|$)
and *PQ.priorities* ($\|\|(-)\|\|$)