

# Derangements

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## Abstract

The Derangements Formula describes the number of fixpoint-free permutations as closed-form formula. This theorem is the 88th theorem of the Top 100 Theorems list.

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## 1 Derangements

**theory** *Derangements*

**imports**

*Complex-Main*

*HOL-Combinatorics.Permutations*

**begin**

### 1.1 Preliminaries

#### 1.1.1 Additions to *HOL.Finite-Set Theory*

**lemma** *card-product-dependent*:

**assumes** *finite S*  $\forall x \in S. \text{finite } (T x)$

**shows**  $\text{card } \{(x, y). x \in S \wedge y \in T x\} = (\sum x \in S. \text{card } (T x))$

**using** *card-SigmaI*[*OF assms, symmetric*] **by** (*auto intro!*: *arg-cong*[**where** *f=card*]  
*simp add: Sigma-def*)

### 1.1.2 Additions to *HOL-Combinatorics.Permutations Theory*

**lemma** *permutes-imp-bij'*:  
**assumes** *p permutes S*  
**shows** *bij p*  
**using** *assms* **by** (*fact permutes-bij*)

**lemma** *permutesE*:  
**assumes** *p permutes S*  
**obtains** *bij p  $\forall x. x \notin S \longrightarrow p x = x$*   
**using** *assms* **by** (*simp add: permutes-def permutes-imp-bij'*)

**lemma** *bij-imp-permutes'*:  
**assumes** *bij p  $\forall x. x \notin A \longrightarrow p x = x$*   
**shows** *p permutes A*  
**using** *assms* *bij-imp-permutes permutes-superset* **by** *force*

**lemma** *permutes-swap*:  
**assumes** *p permutes S*  
**shows** *Fun.swap x y p permutes (insert x (insert y S))*  
**by** (*rule permutes-compose*) (*use assms in  $\langle$ simp-all add: assms permutes-imp-permutes-insert permutes-swap-id $\rangle$* )

**lemma** *bij-extends*:  
*bij p  $\implies p x = x \implies bij (p(x := y, inv p y := x))$*   
**unfolding** *bij-def*  
**proof** (*rule conjI; erule conjE*)  
**assume** *a: inj p p x = x*  
**show** *inj (p(x := y, inv p y := x))*  
**proof** (*intro injI*)  
**fix** *z z'*  
**assume** (*p(x := y, inv p y := x) z = (p(x := y, inv p y := x) z'*)  
**from** *this a* **show** *z = z'*  
**by** (*auto split: if-split-asm simp add: inv-f-eq inj-eq*)  
**qed**

**next**  
**assume** *a: inj p surj p p x = x*  
**{**  
**fix** *x'*  
**from** *a* **have** (*p(x := y, inv p y := x) (((inv p)(y := x, x := inv p y)) x') = x'*)  
**by** (*auto split: if-split-asm*) (*metis surj-f-inv-f*)  
**}**  
**from** *this* **show** *surj (p(x := y, inv p y := x))* **by** (*metis surjI*)  
**qed**

**lemma** *permutes-add-one*:

**assumes**  $p$  permutes  $S$   $x \notin S$   $y \in S$   
**shows**  $p(x := y, \text{inv } p \ y := x)$  permutes  $(\text{insert } x \ S)$   
**proof** (rule *bij-imp-permutes'*)  
**from** *assms* **show** *bij*  $(p(x := y, \text{inv } p \ y := x))$   
**by** (*meson* *bij-extends permutes-def permutes-imp-bij'*)  
**from** *assms* **show**  $\forall z. z \notin \text{insert } x \ S \longrightarrow (p(x := y, \text{inv } p \ y := x)) \ z = z$   
**by** (*metis* *fun-upd-apply insertCI permutes-def permutes-inverses(1)*)  
**qed**

**lemma** *permutations-skip-one*:

**assumes**  $p$  permutes  $S$   $x : S$   
**shows**  $p(x := x, \text{inv } p \ x := p \ x)$  permutes  $(S - \{x\})$   
**proof** (rule *bij-imp-permutes'*)  
**from** *assms* **show**  $\forall z. z \notin S - \{x\} \longrightarrow (p(x := x, \text{inv } p \ x := p \ x)) \ z = z$   
**by** (*auto elim: permutesE simp add: bij-inv-eq-iff*)  
*(simp add: assms(1) permutes-in-image permutes-inv)*  
**from** *assms* **have** *inj*  $(p(x := x, \text{inv } p \ x := p \ x))$   
**by** (*intro injI*) (*auto split: if-split-asm; metis permutes-inverses(2)*)  
**moreover** **have** *surj*  $(p(x := x, \text{inv } p \ x := p \ x))$   
**using** *assms UNIV-I bij-betw-swap-iff permutes-inj permutes-surj surj-f-inv-f*  
**by** (*metis* (*no-types, opaque-lifting*) *Fun.swap-def bij-betw-def*)  
**ultimately show** *bij*  $(p(x := x, \text{inv } p \ x := p \ x))$   
**by** (rule *bijI*)  
**qed**

**lemma** *permutes-drop-cycle-size-two*:

$\langle p \circ \text{Transposition.transpose } x \ (p \ x)$  permutes  $(S - \{x, p \ x\})$   
**if**  $\langle p$  permutes  $S \rangle \langle p \ (p \ x) = x \rangle$   
**proof** (rule *bij-imp-permutes'*)  
**from**  $\langle p$  permutes  $S \rangle$  **have**  $\langle \text{bij } p \rangle$   
**by** (rule *permutes-imp-bij'*)  
**then show**  $\langle \text{bij } (p \circ \text{Transposition.transpose } x \ (p \ x)) \rangle$   
**by** (*simp add: bij-swap-iff*)  
**from**  $\langle p \ (p \ x) = x \rangle \langle p$  permutes  $S \rangle$  **have**  $\langle (p \circ \text{Transposition.transpose } x \ (p \ x))$   
 $y = y \rangle$   
**if**  $\langle y \notin S - \{x, p \ x\} \rangle$  **for**  $y$   
**using** *that* **by** (*cases*  $\langle y \in \{x, p \ x\} \rangle$ ) (*auto simp add: permutes-not-in*)  
**then show**  $\langle \forall y. y \notin S - \{x, p \ x\} \longrightarrow$   
 $(p \circ \text{Transposition.transpose } x \ (p \ x)) \ y = y \rangle$   
**by** *blast*  
**qed**

## 1.2 Fixpoint-Free Permutations

**definition** *derangements* ::  $\text{nat set} \Rightarrow (\text{nat} \Rightarrow \text{nat}) \text{ set}$

**where**

$\text{derangements } S = \{p. p \text{ permutes } S \wedge (\forall x \in S. p \ x \neq x)\}$

**lemma** *derangementsI*:

**assumes**  $p$  permutes  $S \wedge x. x \in S \implies p x \neq x$   
**shows**  $p \in \text{derangements } S$   
**using** *assms* **unfolding** *derangements-def* **by** *auto*

**lemma** *derangementsE*:  
**assumes**  $d : \text{derangements } S$   
**obtains**  $d$  permutes  $S \forall x \in S. d x \neq x$   
**using** *assms* **unfolding** *derangements-def* **by** *auto*

### 1.3 Properties of Derangements

**lemma** *derangements-inv*:  
**assumes**  $d : d \in \text{derangements } S$   
**shows**  $\text{inv } d \in \text{derangements } S$   
**using** *assms*  
**by** (*auto intro!*: *derangementsI elim!*: *derangementsE simp add: permutes-inv permutes-inv-eq*)

**lemma** *derangements-in-image*:  
**assumes**  $d \in \text{derangements } A \ x \in A$   
**shows**  $d x \in A$   
**using** *assms* **by** (*auto elim: derangementsE simp add: permutes-in-image*)

**lemma** *derangements-in-image-strong*:  
**assumes**  $d \in \text{derangements } A \ x \in A$   
**shows**  $d x \in A - \{x\}$   
**using** *assms* **by** (*auto elim: derangementsE simp add: permutes-in-image*)

**lemma** *derangements-inverse-in-image*:  
**assumes**  $d \in \text{derangements } A \ x \in A$   
**shows**  $\text{inv } d x \in A$   
**using** *assms* **by** (*auto intro: derangements-in-image derangements-inv*)

**lemma** *derangements-fixpoint*:  
**assumes**  $d \in \text{derangements } A \ x \notin A$   
**shows**  $d x = x$   
**using** *assms* **by** (*auto elim!: derangementsE simp add: permutes-def*)

**lemma** *derangements-no-fixpoint*:  
**assumes**  $d \in \text{derangements } A \ x \in A$   
**shows**  $d x \neq x$   
**using** *assms* **by** (*auto elim: derangementsE*)

**lemma** *finite-derangements*:  
**assumes** *finite*  $A$   
**shows** *finite* (*derangements*  $A$ )  
**using** *assms* **unfolding** *derangements-def*  
**by** (*auto simp add: finite-permutations*)

## 1.4 Construction of Derangements

**lemma** *derangements-empty*[simp]:

*derangements* {} = {id}

**unfolding** *derangements-def* **by** *auto*

**lemma** *derangements-singleton*[simp]:

*derangements* {x} = {}

**unfolding** *derangements-def* **by** *auto*

**lemma** *derangements-swap*:

**assumes**  $d \in \text{derangements } S$   $x \notin S$   $y \notin S$   $x \neq y$

**shows**  $\text{Fun.swap } x \ y \ d \in \text{derangements } (\text{insert } x \ (\text{insert } y \ S))$

**proof** (*rule derangementsI*)

**from** *assms* **show**  $\text{Fun.swap } x \ y \ d \text{ permutes } (\text{insert } x \ (\text{insert } y \ S))$

**by** (*auto intro: permutes-swap elim: derangementsE*)

**from** *assms* **have**  $s: d \ x = x \ d \ y = y$

**by** (*auto intro: derangements-fixpoint*)

{

**fix**  $x'$

**assume**  $x' : \text{insert } x \ (\text{insert } y \ S)$

**from**  $s$  *assms*  $\langle x \neq y \rangle$  **this** **show**  $\text{Fun.swap } x \ y \ d \ x' \neq x'$

**by** (*cases*  $x' = x$ ; *cases*  $x' = y$ ) (*auto dest: derangements-no-fixpoint*)

}

**qed**

**lemma** *derangements-skip-one*:

**assumes**  $d: d \in \text{derangements } S$  **and**  $x \in S$   $d \ (d \ x) \neq x$

**shows**  $d(x := x, \text{inv } d \ x := d \ x) \in \text{derangements } (S - \{x\})$

**proof** –

**from**  $d$  **have** *bij*:  $\text{bij } d$

**by** (*auto elim: derangementsE simp add: permutes-imp-bij'*)

**from**  $d \ \langle x : S \rangle$  **have** *that*:  $d \ x : S - \{x\}$

**by** (*auto dest: derangements-in-image derangements-no-fixpoint*)

**from**  $d \ \langle d \ (d \ x) \neq x \rangle$  *bij* **have**  $\forall x' \in S - \{x\}. (d(x := x, \text{inv } d \ x := d \ x)) \ x' \neq x'$

**by** (*auto elim!: derangementsE simp add: bij-inv-eq-iff*)

**from**  $d \ \langle x : S \rangle$  **this** **show**  $\text{derangements: } d(x := x, \text{inv } d \ x := d \ x) : \text{derangements } (S - \{x\})$

**by** (*meson derangementsE derangementsI permutations-skip-one*)

**qed**

**lemma** *derangements-add-one*:

**assumes**  $d \in \text{derangements } S$   $x \notin S$   $y \in S$

**shows**  $d(x := y, \text{inv } d \ y := x) \in \text{derangements } (\text{insert } x \ S)$

**proof** (*rule derangementsI*)

**from** *assms* **show**  $d(x := y, \text{inv } d \ y := x) \text{ permutes } (\text{insert } x \ S)$

**by** (*auto intro: permutes-add-one elim: derangementsE*)

**next**

**fix**  $z$

**assume**  $z : \text{insert } x \ S$

```

from assms this derangements-inverse-in-image[OF assms(1), of y]
show ( $d(x := y, \text{inv } d \ y := x)$ )  $z \neq z$  by (auto elim: derangementsE)
qed

```

```

lemma derangements-drop-minimal-cycle:
  assumes  $d \in \text{derangements } S \ d \ (d \ x) = x$ 
  shows  $\text{Fun.swap } x \ (d \ x) \ d \in \text{derangements } (S - \{x, d \ x\})$ 
proof (rule derangementsI)
  from assms show  $\text{Fun.swap } x \ (d \ x) \ d \ \text{permutes } (S - \{x, d \ x\})$ 
    by (meson derangementsE permutes-drop-cycle-size-two)
next
  fix  $y$ 
  assume  $y \in S - \{x, d \ x\}$ 
  from assms this show  $\text{Fun.swap } x \ (d \ x) \ d \ y \neq y$ 
    by (auto elim: derangementsE)
qed

```

## 1.5 Cardinality of Derangements

### 1.5.1 Recursive Characterization

```

fun count-derangements ::  $\text{nat} \Rightarrow \text{nat}$ 
where
  count-derangements 0 = 1
| count-derangements (Suc 0) = 0
| count-derangements (Suc (Suc n)) =  $(n + 1) * (\text{count-derangements } (Suc \ n) + \text{count-derangements } n)$ 

```

```

lemma card-derangements:
  assumes finite S  $\text{card } S = n$ 
  shows  $\text{card } (\text{derangements } S) = \text{count-derangements } n$ 
using assms
proof (induct n arbitrary: S rule: count-derangements.induct)
  case 1
  from this show ?case by auto
next
  case 2
  from this derangements-singleton finite-derangements show ?case
    using Finite-Set.card-0-eq card-eq-SucD count-derangements.simps(2) by fast-force
next
  case (3 n)
  from 3(4) obtain  $x$  where  $x \in S$  using card-eq-SucD insertI1 by auto
  let ?D1 =  $(\lambda(y, d). \text{Fun.swap } x \ y \ d) \ \{ (y, d). \ y \in S \ \& \ y \neq x \ \& \ d : \text{derangements } (S - \{x, y\}) \}$ 
  let ?D2 =  $(\lambda(y, f). \ f(x:=y, \text{inv } f \ y := x)) \ ((S - \{x\}) \times \text{derangements } (S - \{x\}))$ 
  from  $\langle x \in S \rangle$  have subset1: ?D1  $\subseteq$  derangements S
  proof (auto)
    fix  $y \ d$ 

```

```

assume  $y \in S \ y \neq x$ 
assume  $d: d \in \text{derangements } (S - \{x, y\})$ 
from  $\langle x : S \rangle \langle y : S \rangle$  have  $S: S = \text{insert } x (\text{insert } y (S - \{x, y\}))$  by auto
from  $d \langle x : S \rangle \langle y : S \rangle \langle y \neq x \rangle$  show  $\text{Fun.swap } x \ y \ d \in \text{derangements } S$ 
  by (subst S) (auto intro!: derangements-swap)
qed
have subset2: ?D2  $\subseteq \text{derangements } S$ 
proof (rule subsetI, erule imageE, simp split: prod.split-asm, (erule conjE)+)
  fix  $d \ y$ 
  assume  $d : \text{derangements } (S - \{x\}) \ y : S \ y \neq x$ 
  from this have  $d(x := y, \text{inv } d \ y := x) \in \text{derangements } (\text{insert } x (S - \{x\}))$ 
    by (intro derangements-add-one) auto
  from this  $\langle x : S \rangle$  show  $d(x := y, \text{inv } d \ y := x) \in \text{derangements } S$ 
    using insert-Diff by fastforce
qed
have split: derangements S = ?D1  $\cup$  ?D2
proof
  from subset1 subset2 show ?D1  $\cup$  ?D2  $\subseteq \text{derangements } S$  by simp
next
  show  $\text{derangements } S \subseteq \text{?D1} \cup \text{?D2}$ 
  proof
    fix  $d$ 
    assume  $d: d \in \text{derangements } S$ 
    show  $d : \text{?D1} \cup \text{?D2}$ 
    proof (cases d (d x) = x)
      case True
      from  $\langle x : S \rangle \ d$  have  $d \ x \in S \ d \ x \neq x$ 
        by (auto simp add: derangements-in-image derangements-no-fixpoint)
      from  $d \ \text{True}$  have  $\text{Fun.swap } x \ (d \ x) \ d \in \text{derangements } (S - \{x, d \ x\})$ 
        by (rule derangements-drop-minimal-cycle)
      with  $\langle d \ x \in S \rangle \langle d \ x \neq x \rangle$  have  $\langle d \in \text{?D1} \rangle$ 
        by (auto intro!: image-eqI [where x = (d x, Fun.swap x (d x) d)])
      from this show ?thesis by auto
    next
    case False
    from  $d$  have bij: bij d
      by (auto elim: derangementsE simp add: permutes-imp-bij')
    from  $d \langle x : S \rangle$  have that: d x : S - {x}
      by (intro derangements-in-image-strong)
    from  $d \langle x : S \rangle \ \text{False}$  have  $\text{derangements: } d(x:=x, \text{inv } d \ x := d \ x) : \text{derangements } (S - \{x\})$ 
      by (auto intro: derangements-skip-one)
    from this have bij (d(x := x, inv d x := d x))
      by (metis derangementsE permutes-imp-bij'+)
    from this have  $a: \text{inv } (d(x := x, \text{inv } d \ x := d \ x)) \ (d \ x) = \text{inv } d \ x$ 
      by (metis bij-inv-eq-iff fun-upd-same)
    from bij have  $x: d \ (\text{inv } d \ x) = x$  by (meson bij-inv-eq-iff)
    from  $d \ \text{derangements-inv[of } d] \langle x : S \rangle$  have  $\text{inv } d \ x \neq x \ d \ x \neq x$ 
      by (auto dest: derangements-no-fixpoint)
  
```

```

from this a x have d-eq:  $d = d(\text{inv } d \ x := d \ x, \ x := d \ x, \ \text{inv } (d(x := x, \ \text{inv } d \ x := d \ x)) (d \ x) := x)$ 
by auto
from derangements that have  $(d \ x, \ d(x:=x, \ \text{inv } d \ x:=d \ x)) : ((S - \{x\}) \times \text{derangements } (S - \{x\}))$  by auto
from d-eq this have d : ?D2
by (auto intro: image-eqI[where  $x = (d \ x, \ d(x:=x, \ \text{inv } d \ x:=d \ x))$ ])
from this show ?thesis by auto
qed
qed
have no-intersect: ?D1  $\cap$  ?D2 = {}
proof -
have that:  $\bigwedge d. d \in ?D1 \implies d (d \ x) = x$ 
using Diff-iff Diff-insert2 derangements-fixpoint insertI1 swap-apply(2) by
fastforce
have  $\bigwedge d. d \in ?D2 \implies d (d \ x) \neq x$ 
proof -
fix d
assume a:  $d \in ?D2$ 
from a obtain y d' where  $d: d = d'(x := y, \ \text{inv } d' \ y := x)$ 
 $d' \in \text{derangements } (S - \{x\}) \ y \in S - \{x\}$ 
by auto
from d(2) have inv:  $\text{inv } d' \in \text{derangements } (S - \{x\})$ 
by (rule derangements-inv)
from d have inv-x:  $\text{inv } d' \ y \neq x$ 
by (auto dest: derangements-inverse-in-image)
from inv have inv-y:  $\text{inv } d' \ y \neq y$ 
using d(3) derangements-no-fixpoint by blast
from d inv-x have 1:  $d \ x = y$  by auto
from d inv-y have 2:  $d \ y = d' \ y$  by auto
from d(2, 3) have 3:  $d' \ y \in S - \{x\}$ 
by (auto dest: derangements-in-image)
from 1 2 3 show  $d (d \ x) \neq x$  by auto
qed
from this that show ?thesis by blast
qed
have inj: inj-on  $(\lambda(y, f). \ \text{Fun.swap } x \ y \ f) \ \{(y, f). \ y \in S \ \& \ y \neq x \ \& \ f : \text{derangements } (S - \{x, y\})\}$ 
unfolding inj-on-def
by (clarify; metis DiffD2 derangements-fixpoint insertI1 insert-commute swap-apply(1) swap-nilpotent)
have eq:  $\{(y, f). \ y \in S \ \& \ y \neq x \ \& \ f : \text{derangements } (S - \{x, y\})\} = \{(y, f). \ y \in S - \{x\} \ \& \ f : \text{derangements } (S - \{x, y\})\}$ 
by simp
have eq':  $\{(y, f). \ y \in S \ \& \ y \neq x \ \& \ f : \text{derangements } (S - \{x, y\})\} = \text{Sigma } (S - \{x\}) \ (\%y. \ \text{derangements } (S - \{x, y\}))$ 
unfolding Sigma-def by auto
have card:  $\bigwedge y. y \in S - \{x\} \implies \text{card } (\text{derangements } (S - \{x, y\})) = \text{count-derangements}$ 

```



```

n
proof -
  fix y
  assume y ∈ S - {x}
  from 3(3, 4) ⟨x ∈ S⟩ this have card (S - {x, y}) = n
  by (metis Diff-insert2 card-Diff-singleton diff-Suc-1 finite-Diff)
  from 3(3) 3(2)[OF - this] show card (derangements (S - {x, y})) = count-derangements
n by auto
qed
from 3(3, 4) ⟨x : S⟩ have card2: card (S - {x}) = Suc n by (simp add:
card.insert-remove insert-absorb)
from inj have card ?D1 = card {(y, f). y ∈ S - {x} ∧ f ∈ derangements (S -
{x, y})}
by (simp add: card-image)
also from 3(3) have ... = (∑ y∈S - {x}. card (derangements (S - {x, y})))
by (subst card-product-dependent) (simp add: finite-derangements)+
finally have card-1: card ?D1 = (Suc n) * count-derangements n
using card card2 by auto
have inj-2: inj-on (λ(y, f). f(x := y, inv f y := x)) ((S - {x}) × derangements
(S - {x}))
proof -
  {
    fix d d' y y'
    assume 1: d ∈ derangements (S - {x}) d' ∈ derangements (S - {x})
    assume 2: y ∈ S y ≠ x y' ∈ S y' ≠ x
    assume eq: d(x := y, inv d y := x) = d'(x := y', inv d' y' := x)
    from 1 2 eq ⟨x ∈ S⟩ have y: y = y'
    by (metis Diff-insert-absorb derangements-in-image derangements-inv
fun-upd-same fun-upd-twist insert-iff mk-disjoint-insert)
    have d = d'
  }
proof
  fix z
  from 1 have d-x: d x = d' x
  by (auto dest!: derangements-fixpoint)
  from 1 have bij: bij d bij d'
  by (metis derangementsE permutes-imp-bij')+
  from this have d-d: d (inv d y) = y d' (inv d' y') = y'
  by (simp add: bij-is-surj surj-f-inv-f)+
  from 1 2 bij have neq: d (inv d' y') ≠ x ∧ d' (inv d y) ≠ x
  by (metis Diff-iff bij-inv-eq-iff derangements-fixpoint singletonI)
  from eq have (d(x := y, inv d y := x)) z = (d'(x := y', inv d' y' := x)) z
by auto
from y d-x d-d neq this show d z = d' z by (auto split: if-split-asm)
qed
from y this have y = y' & d = d' by auto
}
from this show ?thesis
unfolding inj-on-def by auto
qed

```

```

from  $\mathcal{P}(3)$   $\mathcal{P}(1)[OF - card2]$  have  $card3$ :  $card (derangements (S - \{x\})) =$ 
 $count\_derangements (Suc n)$ 
by auto
from  $\mathcal{P}(3)$   $inj-2$  have  $card-2$ :  $card ?D2 = (Suc n) * count\_derangements (Suc$ 
 $n)$ 
by (simp only: card-image) (auto simp add: card-cartesian-product card3 card2)
from  $\langle finite S \rangle$  have  $finite1$ :  $finite ?D1$ 
unfolding  $eq'$  by (auto intro: finite-derangements)
from  $\langle finite S \rangle$  have  $finite2$ :  $finite ?D2$ 
by (auto intro: finite-cartesian-product finite-derangements)
show  $?case$ 
by (simp add: split card-Un-disjoint finite1 finite2 no-intersect card-1 card-2
 $field-simps$ )
qed

```

### 1.5.2 Closed-Form Characterization

**lemma** *count-derangements*:

$real (count\_derangements n) = fact n * (\sum k \in \{0..n\}. (-1) ^ k / fact k)$

**proof** (*induct n rule: count-derangements.induct*)

**case**  $(\mathcal{P} n)$

**let**  $?f = \lambda n. fact n * (\sum k = 0..n. (-1) ^ k / fact k)$

**have**  $real (count\_derangements (Suc (Suc n))) = (n + 1) * (count\_derangements$ 
 $(n + 1) + count\_derangements n)$

**unfolding** *count-derangements.simps* **by** *simp*

**also** **have**  $... = real (n + 1) * (real (count\_derangements (n + 1)) + real$ 
 $(count\_derangements n))$

**by** (*simp only: of-nat-mult of-nat-add*)

**also** **have**  $... = (n + 1) * (?f (n + 1) + ?f n)$

**unfolding**  $\mathcal{P}(2)$   $\mathcal{P}(1)[unfolded Suc-eq-plus1]$  **..**

**also** **have**  $(n + 1) * (?f (n + 1) + ?f n) = ?f (n + 2)$

**proof**  $-$

**define**  $f$  **where**  $f n = ((fact n) :: real) * (\sum k = 0..n. (-1) ^ k / fact k)$  **for**
 $n$

**have**  $f\text{-eq}$ :  $\bigwedge n. f (n + 1) = (n + 1) * f n + (-1) ^ (n + 1)$

**proof**  $-$

**fix**  $n$

**have**  $?f (n + 1) = (n + 1) * fact n * (\sum k = 0..n. (-1) ^ k / fact k) +$ 
 $fact (n + 1) * ((-1) ^ (n + 1) / fact (n + 1))$

**by** (*simp add: field-simps*)

**also** **have**  $... = (n + 1) * ?f n + (-1) ^ (n + 1)$  **by** (*simp del: One-nat-def*)

**finally** **show**  $?thesis n$  **unfolding**  $f\text{-def}$  **by** *simp*

**qed**

**from**  $this$  **have**  $f\text{-eq}'$ :  $\bigwedge n. (n + 1) * f n = f (n + 1) + (-1) ^ n$  **by** *auto*

**from**  $f\text{-eq}'[of n]$  **have**  $(n + 1) * (f (n + 1) + f n) = ((n + 1) * f (n + 1))$ 
 $+ f (n + 1) + (-1) ^ n$

**by** (*simp only: distrib-left of-nat-add of-nat-1*)

**also** **have**  $... = (n + 2) * f (n + 1) + (-1) ^ (n + 2)$

**by** (*simp del: One-nat-def add-2-eq-Suc' add: algebra-simps*) *simp*

```

    also from f-eq[of n + 1] have ... = f (n + 2) by simp
    finally show ?thesis unfolding f-def by simp
  qed
  finally show ?case by simp
qed (auto)

```

### 1.5.3 Approximation of Cardinality

```

lemma two-power-fact-le-fact:
  assumes n ≥ 1
  shows 2^k * fact n ≤ (fact (n + k) :: 'a :: {semiring-char-0, linordered-semidom})
proof (induction k)
  case (Suc k)
  have 2 ^ Suc k * fact n = 2 * (2 ^ k * fact n) by (simp add: algebra-simps)
  also note Suc.IH
  also from assms have of-nat 1 + of-nat 1 ≤ of-nat n + (of-nat (Suc k) :: 'a)
    by (intro add-mono) (unfold of-nat-le-iff, simp-all)
  hence 2 * (fact (n + k) :: 'a) ≤ of-nat (n + Suc k) * fact (n + k)
    by (intro mult-right-mono) (simp-all add: add-ac)
  also have ... = fact (n + Suc k) by simp
  finally show ?case by - (simp add: mult-left-mono)
qed simp-all

```

```

lemma exp1-approx:
  assumes n > 0
  shows exp (1::real) - (∑ k<n. 1 / fact k) ∈ {0..2 / fact n}
proof (unfold atLeastAtMost-iff, safe)
  have (λk. 1^k / fact k) sums exp (1::real)
    using exp-converges[of 1::real] by (simp add: field-simps)
  from sums-split-initial-segment[OF this, of n]
  have sums: (λk. 1 / fact (n+k)) sums (exp 1 - (∑ k<n. 1 / fact k :: real))
    by (simp add: algebra-simps power-add)
  from assms show (exp 1 - (∑ k<n. 1 / fact k :: real)) ≥ 0
    by (intro sums-le[OF - sums-zero sums]) auto
  show (exp 1 - (∑ k<n. 1 / fact k :: real)) ≤ 2 / fact n
  proof (rule sums-le)
    from assms have (λk. (1 / fact n) * (1 / 2)^k :: real) sums ((1 / fact n) * (1 / (1 - 1 / 2)))
      by (intro sums-mult geometric-sums) simp-all
    also have ... = 2 / fact n by simp
    finally show (λk. 1 / fact n * (1 / 2)^k) sums (2 / fact n :: real) .
  next
  fix k show (1 / fact (n+k)) ≤ (1 / fact n) * (1 / 2 :: real)^k for k
    using two-power-fact-le-fact[of n k] assms by (auto simp: field-simps)
  qed fact+
qed

```

```

lemma exp1-bounds: exp 1 ∈ {8 / 3..11 / 4 :: real}
  using exp1-approx[of 4] by (simp add: eval-nat-numeral)

```

**lemma** *count-derangements-approximation*:

**assumes**  $n \neq 0$

**shows**  $\text{abs}(\text{real}(\text{count-derangements } n) - \text{fact } n / \text{exp } 1) < 1 / 2$

**proof** (*cases*  $n \geq 5$ )

**case** *False*

**from** *assms this* **have**  $n: n = 1 \vee n = 2 \vee n = 3 \vee n = 4$  **by** *auto*

**from** *exp1-bounds* **have**  $1: \text{abs}(\text{real}(\text{count-derangements } 1) - \text{fact } 1 / \text{exp } 1) < 1 / 2$

**by** *simp*

**from** *exp1-bounds* **have**  $2: \text{abs}(\text{real}(\text{count-derangements } 2) - \text{fact } 2 / \text{exp } 1) < 1 / 2$

**by** (*auto simp add: eval-nat-numeral abs-real-def*)

**from** *exp1-bounds* **have**  $3: \text{abs}(\text{real}(\text{count-derangements } 3) - \text{fact } 3 / \text{exp } 1) < 1 / 2$

**by** (*auto simp add: eval-nat-numeral abs-if field-simps*)

**from** *exp1-bounds* **have**  $4: \text{abs}(\text{real}(\text{count-derangements } 4) - \text{fact } 4 / \text{exp } 1) < 1 / 2$

**by** (*auto simp: abs-if field-simps eval-nat-numeral*)

**from**  $1\ 2\ 3\ 4\ n$  **show** *?thesis* **by** *auto*

**next**

**case** *True*

**from** *Maclaurin-exp-le[of - 1 n + 1]*

**obtain**  $t$  **where**  $t: \text{abs}(t :: \text{real}) \leq \text{abs}(-1)$

**and** *exp*:  $\text{exp}(-1) = (\sum m < n + 1. (-1)^m / \text{fact } m) + \text{exp } t / \text{fact}(n + 1) * (-1)^{(n + 1)}$

**by** *blast*

**from** *exp* **have** *sum-eq-exp*:

$(\sum k = 0..n. (-1)^k / \text{fact } k) = \text{exp}(-1) - \text{exp } t / \text{fact}(n + 1) * (-1)^{(n + 1)}$

**by** (*simp add: atLeast0AtMost ivl-disj-un(2)[symmetric]*)

**have** *fact-plus1*:  $\text{fact}(n + 1) = (n + 1) * \text{fact } n$  **by** *simp*

**have** *eq*:  $|\text{real}(\text{count-derangements } n) - \text{fact } n / \text{exp } 1| = \text{exp } t / (n + 1)$

**by** (*simp del: One-nat-def*

*add: count-derangements sum-eq-exp exp-minus inverse-eq-divide algebra-simps abs-mult*)

*(simp add: fact-plus1)*

**from**  $t$  **have**  $\text{exp } t \leq \text{exp } 1$  **by** *simp*

**also from** *exp1-bounds* **have**  $\dots < 3$  **by** *simp*

**finally show** *?thesis* **using**  $\langle n \geq 5 \rangle$  **by** (*simp add: eq*)

**qed**

**theorem** *derangements-formula*:

**assumes**  $n \neq 0$  *finite*  $S$   $\text{card } S = n$

**shows**  $\text{int}(\text{card}(\text{derangements } S)) = \text{round}(\text{fact } n / \text{exp } 1 :: \text{real})$

**using** *count-derangements-approximation[of n] assms*

**by** (*intro round-unique'[symmetric]*) (*auto simp: card-derangements abs-minus-commute*)

**theorem** *derangements-formula'*:

```
assumes  $n \neq 0$  finite  $S$  card  $S = n$ 
shows card (derangements  $S$ ) = nat (round (fact  $n$  / exp 1 :: real))
using derangements-formula[OF assms] by simp
```

end

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