

The Fisher–Yates shuffle

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Abstract

This work defines and proves the correctness of the Fisher–Yates shuffle [1, 2, 3] for shuffling – i. e. producing a random permutation – of a list. The algorithm proceeds by traversing the list and in each step swapping the current element with a random element from the remaining list.

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1 Fisher–Yates shuffle

theory *Fisher-Yates*
imports *HOL-Probability.Probability*
begin

lemma *integral-pmf-of-multiset*:

$A \neq \{\#\} \implies (\int x. (f\ x :: \text{real}) \partial \text{measure-pmf } (\text{pmf-of-multiset } A)) =$
 $(\sum_{x \in \text{set-mset } A}. \text{of-nat } (\text{count } A\ x) * f\ x) / \text{of-nat } (\text{size } A)$
by (*subst integral-measure-pmf[where A = set-mset A]*)
(simp-all add: sum-divide-distrib mult-ac)

lemma *pmf-bind-pmf-of-multiset*:

$A \neq \{\#\} \implies \text{pmf } (\text{pmf-of-multiset } A \gg f) y =$
 $(\sum_{x \in \text{set-mset } A}. \text{real } (\text{count } A\ x) * \text{pmf } (f\ x)\ y) / \text{real } (\text{size } A)$
by (*simp add: pmf-bind integral-pmf-of-multiset*)

lemma *pmf-map-inj-inv*:

assumes *inj-on f (set-pmf p)*
assumes $\bigwedge x. f'\ (f\ x) = x$
shows $\text{pmf } (\text{map-pmf } f\ p)\ x = (\text{if } x \in \text{range } f \text{ then } \text{pmf } p\ (f'\ x) \text{ else } 0)$
proof (*cases x ∈ f ' set-pmf p*)
case *True*
from this obtain y where $y \in \text{set-pmf } p\ x = f\ y$ **by** *blast*
with *assms(1)* **have** $\text{pmf } (\text{map-pmf } f\ p)\ x = \text{pmf } p\ y$
by (*simp add: pmf-map-inj*)
also from y assms(2)[of y] have $y = f'\ x$ **by** *simp*
finally show *?thesis using y by simp*
next
case *False*
hence $x \notin \text{set-pmf } (\text{map-pmf } f\ p)$ **by** *simp*
hence $\text{pmf } (\text{map-pmf } f\ p)\ x = 0$ **by** (*simp add: set-pmf-eq*)
also from False have $0 = (\text{if } x \in \text{range } f \text{ then } \text{pmf } p\ (f'\ x) \text{ else } 0)$
by (*auto simp: assms(2) set-pmf-eq*)
finally show *?thesis .*
qed

1.1 Swapping elements in a list

definition *swap* **where** $\text{swap } xs\ i\ j = xs[i := xs!j, j := xs ! i]$

lemma *length-swap* [*simp*]: $\text{length } (\text{swap } xs\ i\ j) = \text{length } xs$
by (*simp add: swap-def*)

lemma *swap-eq-Nil-iff* [*simp*]: $\text{swap } xs\ i\ j = [] \longleftrightarrow xs = []$
by (*simp add: swap-def*)

lemma *nth-swap*: $i < \text{length } xs \implies j < \text{length } xs \implies$

$swap\ xs\ i\ j\ !\ k = (if\ k = i\ then\ xs\ !\ j\ else\ if\ k = j\ then\ xs\ !\ i\ else\ xs\ !\ k)$
by (*auto simp: swap-def nth-list-update*)

lemma *map-swap*: $i < length\ xs \implies j < length\ xs \implies map\ f\ (swap\ xs\ i\ j) = swap\ (map\ f\ xs)\ i\ j$
by (*simp add: swap-def map-update map-nth*)

lemma *swap-swap*: $i < length\ xs \implies j < length\ xs \implies swap\ (swap\ xs\ i\ j)\ j\ i = xs$
by (*intro nth-equalityI (auto simp: nth-swap nth-list-update)*)

lemma *mset-swap*: $i < length\ xs \implies j < length\ xs \implies mset\ (swap\ xs\ i\ j) = mset\ xs$
by (*simp add: mset-update swap-def nth-list-update*)

lemma *hd-swap-0*: $i < length\ xs \implies hd\ (swap\ xs\ 0\ i) = xs\ !\ i$
unfolding *swap-def* **by** (*subst hd-conv-nth (subst nth-list-update | force)+*)

1.2 Random Permutations

First, we prove the intuitively obvious fact that choosing a random permutation of a multiset can be done by first randomly choosing the first element and then randomly choosing the rest of the list.

lemma *pmf-of-set-permutations-of-multiset-nonempty*:
assumes ($A :: 'a\ multiset \neq \{\#\}$)
shows $pmf\ of\ set\ (permutations\ of\ multiset\ A) =$
 $do\ \{x \leftarrow pmf\ of\ multiset\ A;$
 $\quad xs \leftarrow pmf\ of\ set\ (permutations\ of\ multiset\ (A - \{\#x\#\});$
 $\quad return\ pmf\ (x\#\#xs)$
 $\quad \} (is\ ?lhs = ?rhs)$

proof (*rule pmf-eqI*)

fix $xs :: 'a\ list$

show $pmf\ ?lhs\ xs = pmf\ ?rhs\ xs$

proof (*cases xs ∈ permutations-of-multiset A*)

case *False*

with *assms* **have** $xs \notin set\ pmf\ ?lhs$ **by** *simp*

moreover **from** *assms False* **have** $xs \notin set\ pmf\ ?rhs$

by (*auto simp: permutations-of-multiset-Cons-iff*)

ultimately **show** *?thesis* **by** (*simp add: set-pmf-eq*)

next

case *True*

with *assms* **have** *nonempty*: $xs \neq []$ **by** (*auto dest: permutations-of-multisetD*)

hence *range-Cons*: $xs \in range\ ((\#)\ x) \iff hd\ xs = x$ **for** x

by (*cases xs*) *auto*

from *True nonempty*

have *hd-tl*: $hd\ xs \in \#\ A \wedge tl\ xs \in permutations\ of\ multiset\ (A - \{\#hd\ xs\#\})$

by (*cases xs*) (*auto simp: permutations-of-multiset-Cons-iff*)

from *assms* **have** $pmf\ ?rhs\ xs =$

```

      (∑ x∈set-mset A. real (count A x) * pmf (map-pmf ((#) x)
        (pmf-of-set (permutations-of-multiset (A - {#x#})))) xs) / real (size A)
(is - = ?S / -)
  unfolding map-pmf-def [symmetric] by (simp add: pmf-bind-pmf-of-multiset)
  also have ?S =
    (∑ x∈set-mset A. if x = hd xs then real (count A (hd xs)) /
      real (card (permutations-of-multiset (A - {#hd xs#}))) else 0)
  using range-Cons hd-tl
  by (intro sum.cong refl, subst pmf-map-inj-inv[where f' = tl]) auto
  also have ... = real (count A (hd xs)) /
    real (card (permutations-of-multiset (A - {#hd xs#})))
  using hd-tl by (simp add: sum.delta)
  also from hd-tl have ... = real (size A) / real (card (permutations-of-multiset
A))
    by (simp add: divide-simps real-card-permutations-of-multiset-remove[of hd
xs])
  also have ... / real (size A) = pmf (pmf-of-set (permutations-of-multiset A))
xs
    using assms True by simp
  finally show ?thesis ..
qed
qed

```

1.3 Shuffling Lists

We define shuffling of a list as choosing from the set of all lists that correspond to the same multiset uniformly at random.

definition *shuffle* :: 'a list ⇒ 'a list pmf **where**
shuffle xs = pmf-of-set (permutations-of-multiset (mset xs))

lemma *shuffle-empty* [simp]: *shuffle [] = return-pmf []*
by (simp add: *shuffle-def pmf-of-set-singleton*)

lemma *shuffle-singleton* [simp]: *shuffle [x] = return-pmf [x]*
by (simp add: *shuffle-def pmf-of-set-singleton*)

The crucial ingredient of the Fisher–Yates shuffle is the following lemma, which decomposes a shuffle into swapping the first element of the list with a random element of the remaining list and shuffling the new remaining list.

With a random-access implementation of a list – such as an array – all of the required operations are cheap and the resulting algorithm runs in linear time.

lemma *shuffle-fisher-yates-step*:
assumes *xs-nonempty* [simp]: *xs ≠ []*
shows *shuffle xs =*
 do {*i* ← *pmf-of-set* {..*length xs*};
 let *ys* = *swap xs 0 i*;
zs ← *shuffle (tl ys)*;

```

    return-pmf (hd ys # zs)
  }
proof -
  have shuffle xs = do {x ← pmf-of-multiset (mset xs);
    xs ← pmf-of-set (permutations-of-multiset (mset xs - {#x#}));
    return-pmf (x#xs)
  } unfolding shuffle-def
  by (simp add: pmf-of-set-permutations-of-multiset-nonempty)
  also have pmf-of-multiset (mset xs) =
    pmf-of-multiset (image-mset (!) xs (mset (upt 0 (length xs))))
  by (subst mset-map [symmetric]) (simp add: map-nth)
  also have ... = map-pmf (!) xs (pmf-of-set {..by (subst map-pmf-of-set) (auto simp add: map-pmf-of-set atLeast0LessThan
lessThan-empty-iff)
  also have do {x ← map-pmf (!) xs (pmf-of-set {..by (simp add: map-pmf-def bind-assoc-pmf bind-return-pmf)
  also have ... = do {i ← pmf-of-set {..unfolding Let-def shuffle-def
  by (intro bind-pmf-cong refl, subst (asm) set-pmf-of-set)
  (auto simp: lessThan-empty-iff mset-tl mset-swap hd-swap-0)
  finally show ?thesis by (simp add: Let-def)
qed

```

1.4 Forward Fisher-Yates Shuffle

The actual Fisher–Yates shuffle is now merely a kind of tail-recursive version of decomposition described above. Note that unlike the traditional Fisher–Yates shuffle, we shuffle the list from front to back, which is the more natural way to do it when working with linked lists.

function *fisher-yates-aux* **where**

```

  fisher-yates-aux i xs = (if i + 1 ≥ length xs then return-pmf xs else
    do {j ← pmf-of-set {i..

```

by *auto*

termination by (relation *Wellfounded.measure* ($\lambda(i,xs). \text{length } xs - i$)) *simp-all*

declare *fisher-yates-aux.simps* [*simp del*]

lemma *fisher-yates-aux-correct*:
fisher-yates-aux i $xs = \text{map-pmf } (\lambda ys. \text{take } i \text{ } xs @ ys) (\text{shuffle } (\text{drop } i \text{ } xs))$

proof (*induction* i xs *rule*: *fisher-yates-aux.induct*)
case (1 i xs)
show *?case*
proof (*cases* $i + 1 \geq \text{length } xs$)
case *True*
show *?thesis*
proof (*cases* $i \geq \text{length } xs$)
case *False*
with *True* **have** $\text{length } xs = \text{Suc } i$ **and** $i: i = \text{length } xs - 1$ **by** *simp-all*
hence $xs \neq []$ **by** *auto*
hence $xs = \text{butlast } xs @ [\text{last } xs]$ **by** (*rule* *append-butlast-last-id* [*symmetric*])
also **have** $\text{butlast } xs = \text{take } i \text{ } xs$ **by** (*simp* *add*: *butlast-conv-take* i)
finally **have** $\text{eq: take } i \text{ } xs @ [\text{last } xs] = xs$ **..**
moreover **have** $xs = \text{take } i \text{ } xs @ \text{drop } i \text{ } xs$ **by** *simp*
ultimately **have** $\text{take } i \text{ } xs @ [\text{last } xs] = \text{take } i \text{ } xs @ \text{drop } i \text{ } xs$ **by** (*rule* *trans*)
hence $\text{drop } i \text{ } xs = [\text{last } xs]$ **by** (*subst* (*asm*) *same-append-eq* *simp-all*)
with *True* **show** *?thesis* **by** (*simp* *add*: *eq fisher-yates-aux.simps*)
qed (*simp-all* *add*: *fisher-yates-aux.simps*)
next
case *False*
from *False* **have** *xs-nonempty* [*simp*]: $xs \neq []$ **by** *auto*
have *fisher-yates-aux* i $xs =$
 $\text{pmf-of-set } \{i..<\text{length } xs\} \gg (\lambda j. \text{fisher-yates-aux } (i+1) (\text{swap } xs \ i \ j))$
using *False* **by** (*subst* *fisher-yates-aux.simps* *simp*)
also **have** $\{i..<\text{length } xs\} = ((\lambda j. j + i) ' \{..<\text{length } xs - i\})$
using *False* **by** (*simp* *add*: *lessThan-atLeast0*)
also **from** *False* **have** $\text{pmf-of-set } \dots = \text{map-pmf } (\lambda j. j + i) (\text{pmf-of-set } \{..<\text{length } xs - i\})$
by (*subst* *map-pmf-of-set-inj*) (*simp-all* *add*: *lessThan-empty-iff*)
also **from** *False* **have** $\text{length } xs - i = \text{length } (\text{drop } i \text{ } xs)$ **by** *simp*
also **have** $\text{map-pmf } (\lambda j. j + i) (\text{pmf-of-set } \{..<\text{length } (\text{drop } i \text{ } xs)\}) \gg$
 $(\lambda j. \text{fisher-yates-aux } (i + 1) (\text{swap } xs \ i \ j)) =$
 $\text{pmf-of-set } \{..<\text{length } (\text{drop } i \text{ } xs)\} \gg (\lambda j. \text{fisher-yates-aux } (i + 1)$
 $(\text{swap } xs \ i \ (j+i)))$
by (*simp* *add*: *map-pmf-def* *bind-return-pmf* *bind-assoc-pmf*)
also **have** $\dots = \text{do } \{j \leftarrow \text{pmf-of-set } \{..<\text{length } (\text{drop } i \text{ } xs)\};$
 $\text{let } ys = \text{swap } (\text{drop } i \text{ } xs) \ 0 \ j;$
 $zs \leftarrow \text{shuffle } (\text{tl } ys);$
 $\text{return-pmf } (\text{take } i \text{ } xs @ \text{hd } ys \ \# \ zs)\}$ (*is* $=$ *bind-pmf* $-$ *?T*)
proof (*intro* *bind-pmf-cong* *refl*)
fix j **assume** $j \in \text{set-pmf } (\text{pmf-of-set } \{..<\text{length } (\text{drop } i \text{ } xs)\})$
with *False* **have** $j: j < \text{length } (\text{drop } i \text{ } xs)$ **by** (*simp-all* *add*: *lessThan-empty-iff*)
define ys **where** $ys = \text{swap } xs \ i \ (j + i)$
have *fisher-yates-aux* $(i + 1) \ ys = \text{map-pmf } ((@) (\text{take } (i+1) \ ys)) (\text{shuffle } (\text{drop } (i+1) \ ys))$
using *False* j **unfolding** *ys-def* **by** (*intro* *1.IH*) *simp-all*
also **from** *False* **have** $\text{take } (i+1) \ ys = \text{take } i \ ys @ [\text{hd } (\text{drop } i \ ys)]$

```

    by (simp add: ys-def take-hd-drop)
  also have drop (i+1) ys = tl (drop i ys) by (simp add: ys-def tl-drop drop-Suc)
  also from False j have drop i ys = swap (drop i xs) 0 j
    by (simp add: ys-def swap-def drop-update-swap add-ac)
  also from False j have take i ys = take i xs
    by (simp add: ys-def swap-def)
  finally show fisher-yates-aux (i + 1) ys = ?T j
    by (simp add: ys-def map-pmf-def Let-def bind-assoc-pmf bind-return-pmf)
qed
also from False have ... = map-pmf (λzs. take i xs @ zs) (shuffle (drop i xs))
  by (subst shuffle-fisher-yates-step[of drop i xs])
    (simp-all add: map-pmf-def Let-def bind-return-pmf bind-assoc-pmf)
  finally show ?thesis .
qed
qed

```

definition *fisher-yates* **where**
fisher-yates = *fisher-yates-aux* 0

lemma *fisher-yates-correct*: *fisher-yates* xs = *shuffle* xs
unfolding *fisher-yates-def*
by (*subst fisher-yates-aux-correct*) (*simp-all add: map-pmf-def bind-return-pmf'*)

1.5 Backwards Fisher-Yates Shuffle

We can now easily derive the classical Fisher–Yates shuffle, which goes through the list from back to front and show its equivalence to the forward Fisher–Yates shuffle.

fun *fisher-yates-alt-aux* **where**
fisher-yates-alt-aux i xs = (if i = 0 then return-pmf xs else
do {j ← pmf-of-set {..i};
fisher-yates-alt-aux (i - 1) (swap xs i j)})

declare *fisher-yates-alt-aux.simps* [*simp del*]

lemma *fisher-yates-alt-aux-altdef*:
i < length xs \implies *fisher-yates-alt-aux* i xs =
map-pmf rev (*fisher-yates-aux* (length xs - i - 1) (rev xs))
proof (*induction i xs rule: fisher-yates-alt-aux.induct*)
case (1 i xs)
show ?case
proof (*cases i = 0*)
case False
with 1.premis **have** map-pmf rev (*fisher-yates-aux* (length xs - i - 1) (rev xs))
=
pmf-of-set {length xs - Suc i..<length xs} \gg
(λx. *fisher-yates-aux* (Suc (length xs - Suc i))
(swap (rev xs) (length xs - Suc i) x) \gg
(λx. return-pmf (rev x)))

```

    by (subst fisher-yates-aux.simps) (auto simp: map-pmf-def bind-return-pmf
bind-assoc-pmf)
  also from 1.prem1 False
  have bij: bij-betw ( $\lambda j. \text{length } xs - \text{Suc } j$ )  $\{..i\}$   $\{\text{length } xs - \text{Suc } i..<\text{length } xs\}$ 
    by (intro bij-betwI[where  $g = \lambda j. \text{length } xs - \text{Suc } j$ ]) auto
  from bij have  $\{\text{length } xs - \text{Suc } i..<\text{length } xs\} = (\lambda j. \text{length } xs - \text{Suc } j) \text{ ' } \{..i\}$ 
    by (simp add: bij-betw-def)
  also from bij have pmf-of-set ... = map-pmf ( $\lambda j. \text{length } xs - \text{Suc } j$ ) (pmf-of-set
 $\{..i\}$ )
    by (subst map-pmf-of-set-inj) (auto simp: bij-betw-def)
  also have map-pmf ( $\lambda j. \text{length } xs - \text{Suc } j$ ) (pmf-of-set  $\{..i\}$ )  $\ggg$ 
    ( $\lambda x. \text{fisher-yates-aux } (\text{Suc } (\text{length } xs - \text{Suc } i))$ 
      ( $\text{swap } (\text{rev } xs) (\text{length } xs - \text{Suc } i) x$ )  $\ggg$  ( $\lambda x. \text{return-pmf } (\text{rev } x)$ ))
=
    pmf-of-set  $\{..i\}$   $\ggg$  ( $\lambda x. \text{map-pmf } \text{rev } ($ 
      fisher-yates-aux ( $\text{length } xs - i$ ) ( $\text{rev } (\text{swap } xs \ i \ x)$ ))
  using 1.prem1 False
  by (auto simp add: map-pmf-def bind-assoc-pmf bind-return-pmf Suc-diff-Suc
swap-def rev-update rev-nth intro!: bind-pmf-cong)
  also have ... = pmf-of-set  $\{..i\}$   $\ggg$  ( $\lambda j. \text{fisher-yates-alt-aux } (i - 1) (\text{swap } xs$ 
 $i \ j)$ )
    using 1.prem1 False 1.IH [symmetric] by (auto intro!: bind-pmf-cong)
  also from 1.prem1 False have ... = fisher-yates-alt-aux  $i \ xs$ 
    by (subst fisher-yates-alt-aux.simps[of  $i$ ]) simp-all
  finally show ?thesis ..
qed (insert 1.prem1, simp-all add: fisher-yates-aux.simps fisher-yates-alt-aux.simps)
qed

```

definition *fisher-yates-alt* **where**

fisher-yates-alt $xs = \text{fisher-yates-alt-aux } (\text{length } xs - 1) \ xs$

lemma *fisher-yates-alt-aux-correct*:

fisher-yates-alt $xs = \text{shuffle } xs$

proof (cases $xs = []$)

case True

thus ?thesis

by (simp add: fisher-yates-alt-def fisher-yates-alt-aux.simps)

next

case False

thus ?thesis **unfolding** *fisher-yates-alt-def*

by (subst fisher-yates-alt-aux-altdef)

(simp-all add: fisher-yates-aux-correct shuffle-def map-pmf-of-set-inj)

qed

1.6 Code generation test

Isabelle's code generator allows us to produce executable code both for *shuffle* and for *fisher-yates* and *fisher-yates-alt*. However, this code does not produce a random sample (i.e. a single randomly permuted list) – which

is, in fact, the only purpose of the Fisher–Yates algorithm – but the entire probability distribution consisting of $n!$ lists, each with probability $1/n!$.

In the future, it would be nice if Isabelle also had some code generation facility that supports generating sampling code.

```
value [code] shuffle "abcd"  
value [code] fisher-yates "abcd"  
value [code] fisher-yates-alt "abcd"
```

end

References

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