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theory Problem-5
imports
  Main
  HOL-Library.Multiset
  HOL-Number-Theory.Number-Theory
  Common.Future-Library
begin

```

The Bank of Bath issues coins with an H on one side and a T on the other. Harry has n of these coins arranged in a line from left to right. He repeatedly performs the following operation: if there are exactly $k > 0$ coins showing H , then he turns over the k th coin from the left; otherwise, all coins show T and he stops.

a) Show that, for each initial configuration, Harry stops after a finite number of operations.

b) Find the average number of steps Harry will take over all 2^n possible initial configurations.

1 Definitions

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datatype coin = H | T

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fun flip :: coin  $\Rightarrow$  coin where
  flip H = T |
  flip T = H

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definition headcount :: coin list  $\Rightarrow$  nat where
  headcount cs = count (mset cs) H

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definition step :: coin list  $\Rightarrow$  coin list where
  step x = (case headcount x of
    0  $\Rightarrow$  x |
    Suc n  $\Rightarrow$  x[n := flip (x ! n)])

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2 A closed formula for the number of steps

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definition heads :: coin list  $\Rightarrow$  nat set where
  heads cs = {n. n < length cs  $\wedge$  cs ! n = H}

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lemma finite-heads[simp]: finite (heads cs)
unfolding heads-def by simp

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lemma headcount-heads: headcount cs = card (heads cs)
unfolding headcount-def heads-def
by (smt Collect-cong count-mset length-filter-conv-card)

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lemma headcount-le: headcount cs  $\leq$  length cs
by (metis count-mset headcount-def length-filter-le)

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definition steps :: coin list  $\Rightarrow$  nat where
  steps cs = headcount cs + 2* $\sum$  (heads cs) - 2* $\sum$  {0.. $\leq$ headcount cs}

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3 Lifting steps from nat to int

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lemma steps-sub:
  2* $\sum$  {0.. $\leq$ headcount cs}  $\leq$  2* $\sum$  (heads cs)
using sum-min unfolding headcount-heads by simp

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lemma steps-alt:
  int (steps cs) = int (headcount cs) + int (2* $\sum$  (heads cs)) - int (2* $\sum$  {0.. $\leq$ headcount cs})
proof -

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have int (headcount cs) + int (2 *  $\sum$  (heads cs))
   $\geq$  int (2 *  $\sum$  {0.. $\text{headcount cs}$ })
using steps-sub[of cs] by linarith
then show ?thesis
  unfolding steps-def int-ops(6) int-plus
  by auto
qed

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4 *steps* describes the behavior of *step*

lemma *step-stopped*:

$H \notin \text{set } x \implies \text{steps } x = 0$

proof –

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assume  $H \notin \text{set } x$ 
then have headcount  $x = 0$  unfolding headcount-def
  by simp
with finite-heads and headcount-heads have heads  $x = \{\}$  by simp
show steps  $x = 0$ 
  using  $\langle \text{heads } x = \{\} \rangle$  and  $\langle \text{headcount } x = 0 \rangle$  by (simp add: steps-def)

```

qed

lemma *step-running*:

assumes $H \in \text{set } x$

shows steps $x = \text{Suc } (\text{steps } (\text{step } x))$

proof –

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from assms have headcount  $x \neq 0$ 
  unfolding headcount-def by simp
then obtain  $n$  where headcount: headcount  $x = \text{Suc } n$ 
  using not0-implies-Suc by blast
with assms have  $x'$ : step  $x = x[n := \text{flip } (x ! n)]$  unfolding step-def by simp

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from headcount and headcount-le have  $n\text{-lt}$ :  $n < \text{length } x$ 
  by (metis Suc-le-lessD)

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show ?thesis

proof (cases $x ! n$)

case H

then have heads (step x) = heads $x - \{n\}$

using $x' n\text{-lt}$ unfolding heads-def

by (auto simp add: nth-list-update)

moreover have $n \in \text{heads } x$

using $\langle x ! n = H \rangle n\text{-lt}$ unfolding heads-def

by auto

ultimately have $\sum (\text{heads } (\text{step } x)) = \sum (\text{heads } x) - n$

by (simp add: sum-diff1-nat)

moreover have $n \leq \sum (\text{heads } x)$

using $\langle n \in \text{heads } x \rangle$ member-le-sum by fastforce

ultimately have *: $\sum (\text{heads } x) = \sum (\text{heads } (\text{step } x)) + n$

by simp

from $\langle n \in \text{heads } x \rangle$

have headcount $x = \text{Suc } (\text{headcount } (\text{step } x))$

unfolding headcount-heads $\langle \text{heads } (\text{step } x) = \text{heads } x - \{n\} \rangle$

by (intro card.remove) simp

with headcount have headcount (step x) = n by simp

with * have int (steps x) = int (steps (step x)) + 1

unfolding steps-alt

by (simp add: headcount)

thus ?thesis by simp

next

case T

then have heads (step x) = insert n (heads x)

using $x' n\text{-lt}$ unfolding heads-def

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    by (auto simp add: nth-list-update)
  moreover have  $n \notin \text{heads } x$ 
    using  $\langle x ! n = T \rangle$  n-lt unfolding heads-def
    by auto
  ultimately have  $\sum (\text{heads } (\text{step } x)) = \sum (\text{heads } x) + n$ 
    by simp
  moreover have  $\text{headcount } (\text{step } x) = \text{Suc } (\text{headcount } x)$ 
    unfolding headcount-heads  $\langle \text{heads } (\text{step } x) = \text{insert } n (\text{heads } x) \rangle$ 
    using  $\langle n \notin \text{heads } x \rangle$ 
    by (intro card-insert-disjoint; auto)
  ultimately have  $\text{int } (\text{steps } x) = \text{int } (\text{steps } (\text{step } x)) + 1$ 
    unfolding steps-alt
    by (simp add: headcount)
  thus ?thesis by simp
qed
qed

```

corollary *steps-stopped-iff*:
 $H \notin \text{set } x \longleftrightarrow \text{steps } x = 0$
 using step-stopped step-running by auto

The above two lemmas can be combined using the saturating property of *nat* subtraction.

lemma *stopped-idempotent*:
 $H \notin \text{set } x \implies \text{step } x = x$
proof –
 assume $H \notin \text{set } x$
 then have $\text{headcount } x = 0$ unfolding headcount-def by simp
 thus $\text{step } x = x$ unfolding step-def by simp
qed

lemma *steps-decreases*:
 $\text{steps } (\text{step } x) = \text{steps } x - 1$
apply (cases $H \in \text{set } x$)
 using step-running step-stopped stopped-idempotent by auto

lemma *step-funpow[simp]*:
 $\text{steps } ((\text{step}^{\sim k}) x) = \text{steps } x - k$
apply (induction k)
 by (auto simp add: steps-decreases)

corollary *terminates*:
 $H \notin \text{set } ((\text{step}^{\sim \text{steps } x}) x)$
 by (simp add: steps-stopped-iff)

proposition *steps-is-least*:
 $(\text{LEAST } k. H \notin \text{set } ((\text{step}^{\sim k}) x)) = \text{steps } x$
proof (intro Least-equality)
 show $H \notin \text{set } ((\text{step}^{\sim \text{steps } x}) x)$ by (fact terminates)
 fix y
 assume $y\text{-end}: H \notin \text{set } ((\text{step}^{\sim y}) x)$
 {
 assume $y < \text{steps } x$
 then have $\text{steps } ((\text{step}^{\sim y}) x) \neq 0$
 by simp
 with $y\text{-end}$ have False by (simp add: steps-stopped-iff)
 }
 then show $\text{steps } x \leq y$
 by fastforce
qed

5 Average step count

definition *positions* :: nat \Rightarrow coin list set **where**
positions $n = \{cs. \text{length } cs = n\}$

definition *step-avg* :: nat \Rightarrow real **where**
step-avg $n = (\sum p \in \text{positions } n. \text{steps } p) / \text{card } (\text{positions } n)$

lemma *coin-finite*: finite (UNIV::coin set)
and *coin-card*: card (UNIV::coin set) = 2

proof –
have $x = H \vee x = T$ **for** $x :: \text{coin}$
by (cases x) *auto*
hence (UNIV::coin set) = {H, T}
by *auto*
moreover **have** finite {H, T}
by *simp*
ultimately **show** finite (UNIV::coin set)
by *simp*
have card {H, T} = 2
by *simp*
with (UNIV = {H, T}) **show** card (UNIV::coin set) = 2
by *simp*
qed

lemma *numpos*: card (positions n) = 2^n
unfolding *positions-def*
using *card-lists-length-eq* [OF *coin-finite*]
by (auto *simp* add: *coin-card*)

corollary *finite-positions*[intro]: finite (positions n)
using *card.infinite numpos* **by** *fastforce*

lemma *real-sum*: real (sum f S) = sum (real $\circ f$) S
using *int-sum of-int-sum* **by** *simp*

lemma *heads-inj*: length $a = \text{length } b \implies \text{heads } a = \text{heads } b \implies a = b$

proof –
assume *len*: length $a = \text{length } b$ **and** *heads-eq*: heads $a = \text{heads } b$
{
fix n
assume $n < \text{length } a$
from *heads-eq* **have** *: $n < \text{length } a \wedge a ! n = H \longleftrightarrow n < \text{length } b \wedge b ! n = H$
unfolding *heads-def* **by** *auto*
hence $a ! n = H \longleftrightarrow b ! n = H$
using *len* ($n < \text{length } a$) **by** *simp*
hence $a ! n = b ! n$
by (*metis flip.cases*)
}
with *list-eq-iff-nth-eq len* **show** ?thesis
by *blast*
qed

corollary *heads-inj-on-positions*: inj-on heads (positions n)
using *heads-inj* **by** (auto *simp* add: *positions-def intro: inj-onI*)

lemma *heads-positions-subset*:
 $h \in \text{heads } \text{'positions } n \longleftrightarrow h \subseteq \{0..<n\}$

proof
assume $h: h \subseteq \{0..<n\}$
let ?L = map ($\lambda n. \text{if } n \in h \text{ then } H \text{ else } T$) [0.. n]
have ?L $\in \text{positions } n$
unfolding *positions-def* **by** *simp*

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moreover have heads ?L = h
  unfolding heads-def
  using h apply auto
  by (meson coin.simps(2))
ultimately show h ∈ heads ‘ positions n by auto
qed (auto simp add: positions-def heads-def)

lemma card-headcount[simp]: card {p ∈ positions n. headcount p = k} = n choose k
  (is card ?S = -)
proof -
  have ?S = {p ∈ positions n. card (heads p) = k}
    unfolding headcount-heads..
  also have card ... = card {h ∈ heads ‘ positions n. card h = k}
    (is card ?A = card ?B)
  proof (intro bij-betw-same-card bij-betw-imageI)
    show inj-on heads ?A
    by (metis (mono-tags, lifting) inj-onD inj-onI mem-Collect-eq heads-inj-on-positions)
  qed auto
  also have ... = card {h. h ⊆ {0..using heads-positions-subset by auto
  also have ... = n choose k
    by (simp add: n-subsets)
  finally show ?thesis.
qed

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lemma headcount-image[iff]: headcount ‘ positions n ⊆ {0..unfolding positions-def
  by (auto simp: headcount-le)

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lemma part1: (∑ p ∈ positions n. headcount p) = n * 2(n-1)
proof -
  have (∑ p ∈ positions n. headcount p) = (∑ k ∈ {0..apply (intro sum-count[where f=λx. x and g=headcount, OF finite-positions, simplified])
    by (simp, fact headcount-image)
  also have ... = (∑ k ≤ n. (n choose k) * k)
    using atMost-atLeast0 by simp
  finally show ?thesis
    by (simp add: choose-linear-sum ac-simps)
qed

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lemma part3: (∑ p ∈ positions n. 2 * ∑ {0..(n-2)
proof -
  have *: ∑ {0..for n::nat
    by (cases n; auto simp: atLeastLessThanSuc-atLeastAtMost)
  have (∑ p ∈ positions n. 2 * ∑ {0..apply (intro sum-count)
    by auto
  also have ... = (∑ k ∈ {0..by (simp add: * gauss-sum-nat)
  also have ... = (∑ k ∈ {0..proof -
    have (k-1) * Suc (k-1) = (k-1) * k for k::nat
      by (cases k; auto)
    thus ?thesis
      by (simp add: ac-simps)
  qed
  also have ... = (∑ k ∈ {2..proof (cases n < 2)
  case False
  then have {0..by auto

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moreover have  $(\sum k \in \{0, 1\}. (n \text{ choose } k) * (k - 1) * k) = 0$ 
  by auto
ultimately show ?thesis by simp
qed auto
also have  $\dots = (\sum k \in \{2..n\}. ((n-2) \text{ choose } (k-2)) * n * (n - 1))$ 
proof –
  {
    fix  $k :: \text{nat}$ 
    assume  $k \geq 2$ 
    then obtain  $k'$  where  $k = \text{Suc } (\text{Suc } k')$ 
      using add-2-eq-Suc le-Suc-ex by blast
    hence  $(k - 1) * (k * (n \text{ choose } k)) = (n - 1) * n * ((n-2) \text{ choose } (k-2))$ 
      by (auto simp del: mult-Suc-right mult-Suc simp add: binomial-absorption numeral-eq-Suc)
  }
  thus ?thesis
  by (intro sum.cong; auto simp: ac-simps)
qed
also have  $\dots = n * (n - 1) * (\sum k \in \{2..n\}. (n - 2) \text{ choose } (k - 2))$ 
  by (simp flip: sum-distrib-right)
also have  $\dots = n * (n - 1) * (\sum k \in \{0..n-2\}. (n - 2) \text{ choose } k)$ 
proof (cases n < 2)
  case False
    then obtain  $n'$  where  $n = \text{Suc } (\text{Suc } n')$ 
      by (metis less-iff-Suc-add not-less-eq numeral-2-eq-2)
    then have [simp]:  $(\sum k \in \{2..n\}. f\ k) = (\sum k \in \{0..n-2\}. f\ (k + 2))$  for  $f :: \text{nat} \Rightarrow \text{nat}$ 
      using sum.shift-bounds-cl-nat-ivl [where  $k=2$  and  $m=0$  and  $n=n'$  and  $g=f$ ]
      by (simp add: numeral-eq-Suc)
    show ?thesis by simp
  qed auto
also have  $\dots = n * (n - 1) * 2^{(n-2)}$ 
  using atMost-atLeast0 choose-row-sum by simp
finally show ?thesis.
qed

lemma part2:  $(\sum p \in \text{positions } n. 2 * \sum (\text{heads } p)) = n * (n-1) * 2^{(n-1)}$ 
proof –
  have  $(\sum p \in \text{positions } n. 2 * \sum (\text{heads } p)) = (\sum h \in \text{heads ' positions } n. 2 * \sum h)$ 
    using sum.reindex[OF heads-inj-on-positions, symmetric, where n=n and g=λh. 2*∑ h]
    by simp
also have  $\dots = (\sum h \in \text{Pow } \{0..<n\}. 2 * \sum h)$ 
proof –
  have heads ' positions  $n = \text{Pow } \{0..<n\}$ 
    using heads-positions-subset by auto
  thus ?thesis by simp
qed
also have  $\dots = n * (n - 1) * 2^{(n - 1)}$ 
proof (induction n)
  case (Suc n)
    note  $IH = \text{this}$ 
    show ?case
    proof (cases n)
    case 0
      then show ?thesis by simp eval
    next
      case (Suc n')
      have  $\text{Pow } \{0..<\text{Suc } n\} = \text{Pow } \{0..<n\} \cup \text{insert } n \text{ ' Pow } \{0..<n\}$ 
        by (simp add: Pow-insert atLeast0-lessThan-Suc)
      moreover have  $\text{Pow } \{0..<n\} \cap \text{insert } n \text{ ' Pow } \{0..<n\} = \{\}$ 
        by auto
      moreover have inj-on  $(\text{insert } n) (\text{Pow } \{0..<n\})$ 
        by (force intro: inj-onI)
      moreover have  $x \in \text{Pow } \{0..<n\} \implies \sum (\text{insert } n\ x) = n + \sum x$  for  $x$ 
        apply (intro sum.insert)

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    apply auto
    using infinite-super by blast
    ultimately show ?thesis
    apply (simp add: sum.union-disjoint sum.reindex sum.distrib Suc.IH card-Pow)
    by (simp add: ⟨n = Suc n⟩ algebra-simps)
  qed
qed simp
finally show ?thesis.
qed

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lemma stepsum:
  sum steps (positions n)
  = 2^(n-1) * (n^2 + n) div 2
  (is ?L = ?R)
proof -
  have int (∑ p ∈ positions n. steps p)
  = int (∑ p ∈ positions n. headcount p)
  + int (∑ p ∈ positions n. 2 * ∑ (heads p))
  - int (∑ p ∈ positions n. 2 * ∑ {0..<headcount p})
  unfolding int-sum steps-alt sum-subtractf sum.distrib..
  hence int ?L = int ?R
  unfolding part1 part2 part3
  apply (cases n rule: fib.cases)
  by (auto simp add: algebra-simps power2-eq-square)
  thus ?L = ?R by linarith
qed

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theorem avg-steps:
  step-avg n = real (n^2 + n) / 4
proof -
  have even: even (n^2 + n) unfolding power2-eq-square by simp
  hence real (2^(n-1) * (n^2 + n) div 2) / real (2^n)
    = real (2^(n-1) * ((n^2 + n) div 2)) / real (2^n)
    by fastforce
  also have ... = 2^(n-1) * real (n^2 + n) / 2^Suc n
    by (simp add: real-of-nat-div[OF even])
  also have ... = real (n^2 + n) / 4
    apply (cases n)
    by auto
  finally show ?thesis
    unfolding step-avg-def numpos stepsum.
  qed

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end