

Name (printed): _____

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Directions: This exam booklet contains both the standard and advanced track questions. Questions with no annotation are for *both* tracks. Other questions are marked "Standard Only" or "Advanced Only." *Do not waste time answering questions intended for the other track.*

Mark the box of the track you are following. (If you are following one track but want to move to the other now, please mark the box for the track you *want* to be on and write a note on this page telling us that we should switch you to this track.)

Standard

Advanced

NOTE: Throughout this exam, we use informal notation for Imp boolean expressions. For example, we write $X \langle \rangle Y$ instead of $BNot (BEq X Y)$.

1. (5 points)

1. If c is equivalent to $c;;c$, then $c;;c$ is equivalent to $c;;c;;c$.

True *False*

2. If $c1;;c2$ is equivalent to $c2;;c1$, then $c1$ is equivalent to $c2$.

True *False*

3. The following Hoare triple is valid.

$\{\{ \text{True} \} Y ::= X + 1; \text{WHILE } X \langle \rangle 0 \text{ DO } X ::= X - 1 \text{ END } \{ Y = X + 1 \}$

True *False*

4. The following two programs are equivalent:

`WHILE X <> 0 DO SKIP END`

and

`WHILE X <> 0 DO Y ::= Y - 1 END`

True *False*

5. `normal_form` is a syntactic concept that is defined by looking at the form of a term, while `value` is a semantic concept that is defined by looking at how the term steps.

True *False*

2. (10 points) Recall that the assertion P appearing in the `hoare_while` rule is called the *loop invariant*. For each loop shown below, circle *each* assertion that is a valid loop invariant. (There may be zero or more than one of them.)

1. WHILE $X < 100$ DO $X ::= X + 1$ END

- (a) $X > 10$
- (b) $X < 100$
- (c) $X \leq 100$
- (d) $X > 100$

2. WHILE $X > 10$ DO $X ::= X + 1$ END

- (a) $X > 10$
- (b) $X < 100$
- (c) $X \leq 100$
- (d) $X \geq 5$
- (e) **False**
- (f) **True**

3. WHILE $Y > 0$ DO $Y ::= Y - 1$; ; $Z ::= Z + X$ END

- (a) $X > 10$
- (b) $Y > 10$
- (c) $W = Z + (X * Y)$
- (d) $Z < Y$

3. **[Standard Only]** (12 points) Are the following Hoare logic rules of inference valid? Write *Valid* or *Invalid*. Additionally, if the rule is invalid, give a counterexample—i.e., a concrete P , Q , c , st , and st' such that (1) $\{P\} c \{Q\}$ according to the proposed rule, (2) $c / st \setminus st'$, (3) P holds of st , and (4) Q does not hold of st' .

1.

$$\frac{\{P\} c;;c \{P\}}{\{P\} c \{P\}} \quad (\text{hoare_two_to_one})$$

2.

$$\frac{\{P \wedge b\} c \{Q\}}{\{P\} \text{ WHILE } b \text{ DO } c \text{ END } \{Q \wedge \sim b\}} \quad (\text{hoare_whilealt})$$

3.

$$\frac{}{\{P\} X ::= a \{P[X \mapsto a]\}} \quad (\text{hoare_assn_forward})$$

4. **[Advanced Only]** (13 points) The Imp command `WHILE True DO SKIP END` never terminates. Write a careful, informal proof of this fact. In other words, prove:

$$\forall st\ st', \sim(\text{WHILE True DO SKIP END}/st \Downarrow st')$$

5. (15 points) Recall the definition of what it means for a term t to be a *normal form* of a relation R .

`Definition normal_form {X:Type} (R:relation X) (t:X) : Prop :=
 ~ exists t', R t t'.`

1. Give a complete and precise description, in English, of all the Imp arithmetic expressions $a : \text{aexp}$ that are normal forms for the `astep` relation (i.e., for which the proposition `normal_form (astep st) a` holds for all states st).

2. Give a complete and precise description of all the Imp commands c and states st such that the pair (c, st) is a normal form for the `cstep` relation.

3. Define informally what it means for a step relation to be *normalizing*.

4. Give an informal definition of strong progress.

5. Does strong progress imply termination?

Yes *No*

6. (10 points) Suppose we extend the Imp language with a simple mechanism for throwing and catching exceptions. The new command `THROW` throws an exception, while the command `TRY c1 CATCH c2 END` runs `c1` and—if `c1` terminates normally—simply terminates in the same final state; if `c1` throws an exception, on the other hand, `TRY c1 CATCH c2 END` will then run `c2` (starting from the state in which the exception was thrown in `c1`). For example:

- `TRY X ::= 5 CATCH X ::= 42 END` terminates normally with $X = 5$
- `(TRY X ::= 5 CATCH X ::= 42 END); THROW` raises an exception with $X = 5$
- `TRY X ::= 5;; THROW CATCH X ::= X+1 END` terminates normally with $X = 6$
- `TRY X ::= 5;; THROW CATCH X ::= X+1;; THROW END` raises an exception with $X = 6$
- `TRY (TRY X ::= 5;; THROW CATCH X ::= X+1;; THROW) CATCH X ::= X+1 END` terminates normally with $X = 7$

The syntax of Imp is extended as follows:

```
Inductive com : Type :=
  | CSkip : com
  | CStop : com          (* <-- new *)
  | CTry : com -> com -> com  (* <-- new *)
  | CAss : id -> aexp -> com
  | CSeq : com -> com -> com
  | CIf : bexp -> com -> com -> com
  | CWhile : bexp -> com -> com.
```

Notation "'THROW'" :=

`CStop`.

Notation "'TRY' c1 'CATCH' c2 'END'" :=

`(CTry c1 c2)` (at level 80, right associativity).

To define the evaluation relation, we need to distinguish between (1) normal termination of a command and (2) raising an exception. We introduce the following datatype for this purpose:

```
Inductive status : Type :=
```

```
  | SNormal : status
```

```
  | SThrow : status.
```

The evaluation relation is extended to include a **status**: we write `c / st \\
s / st'` to mean that running command `c` in state `st` terminates with status `s` and final state `st'`.

(continued...)

Intuitively, $c / st \ \backslash \ s / st'$ means that, if c is started in state st , then it terminates in state st' and the status s signals either that an exception has been raised ($s = SThrow$) or that execution terminated normally ($s = SNormal$).

- If the command is `SKIP`, then the state doesn't change and execution of any enclosing loop terminates normally.
- If the command is `THROW`, the state stays unchanged but we signal an exception.
- If the command is an assignment, then we update the binding for that variable in the state accordingly and signal that execution terminates normally.
- If the command is of the form `IFB b THEN c1 ELSE c2 FI`, then execution proceeds as in the original semantics of `Imp`, except that we also propagate the status from the execution of whichever branch was taken.
- If the command is a sequence `c1 ; c2`, we first execute `c1`. If this terminates with status `SThrow`, we skip the execution of `c2` and terminate the whole command with status `SThrow`; the resulting state is the one resulting from `c1`. Otherwise, we execute `c2` as usual and yield its final state and status.
- If the command is `TRY c1 CATCH c2 END`, we begin by executing `c1`; if it terminates normally, then the whole `TRY` terminates in the same state and with normal status; if it terminates with an exception, we execute `c2` (in the state resulting from `c1`) and yield its final state and status.
- Finally, for a loop of the form `WHILE b DO c END`, when `b` evaluates to true, we execute `c` and check the status it returns. If it is `SNormal`, execution proceeds as in the original semantics. Otherwise, we stop the execution of the loop and yield status `SThrow`.

Based on the above description, complete the formal definition of the `ceval` relation on the following page.

```

Inductive ceval : com -> state -> status -> state -> Prop :=
| E_Skip : forall st,
  CSkip / st \\ SNormal / st
| E_Stop : forall st,
  CStop / st \\ SThrow / st
| E_Ass  : forall st a1 n x,
  aeval st a1 = n ->
  (x ::= a1) / st \\ SNormal / (t_update st X n)
| E_If   : forall c1 c2 b st st' s,
  (if beval st b then c1 else c2) / st \\ s / st' ->
  (IFB b THEN c1 ELSE c2 FI) / st \\ s / st'
| E_SeqContinue : forall c1 c2 st st' st'' s,
  c1 / st \\ SNormal / st' ->
  c2 / st' \\ s / st'' ->
  (c1 ;; c2) / st \\ s / st''
| E_SeqStop : forall c1 c2 st st',
  c1 / st \\ SThrow / st' ->
  (c1 ;; c2) / st \\ SThrow / st'

| E_TryContinue : forall c1 c2 st st',

| E_TryStop : forall c1 c2 st st' st'' s,

| E_WhileEnd : forall c b st,

| E_WhileContinue : forall c b st st' st'' s,

| E_WhileStop : forall c b st st',

```

7. (9 points) (*Continuation of previous problem.*) Now we need to extend Hoare logic appropriately to deal with the possibility of exceptions. We begin by introducing *Hoare quads*, which are just like Hoare triples but have one additional assertion. The Hoare quad $\{\{P\}\} c \{\{Q\}\} \{\{R\}\}$ is read “If command c is run in a state satisfying P , then (1) if it terminates normally, the final state will satisfy Q , and (2) if it raises an exception (that is not caught by an internal TRY), the final state will satisfy R .” In Coq:

Definition hoare_quad

```
(P:Assertion) (c:com) (Q:Assertion) (R:Assertion) : Prop :=
forall st st' s,
  c / st \ \ s / st' ->
  P st ->
  (s = SNormal /\ Q st') \ / (s = SThrow /\ R st').
```

Notation " $\{\{P\}\} c \{\{Q\}\} \{\{R\}\}$ " :=

```
(hoare_quad P c Q R) (at level 90, c at next level)
: hoare_spec_scope.
```

For each of the following Hoare quads state whether it is valid or invalid. If it is invalid, give a counterexample.

1. $\{\{True\}\} \text{TRY } (X ::= 1;; \text{THROW}) \text{CATCH THROW END } \{\{False\}\} \{\{X = 1\}\}$

2. $\{\{True\}\} \text{IFB } Y=1 \text{ THEN THROW ELSE } X ::= 2 \text{ FI } \{\{X = 2\}\} \{\{Y = 1\}\}$

3. $\{\{Z = 10\}\} \text{WHILE } Z>0 \text{ DO } (\text{IFB } Z=1 \text{ THEN THROW ELSE } Z ::= Z-1 \text{ FI}) \text{ END } \{\{Z = 1\}\} \{\{Z = 0\}\}$

8. **[Advanced Only]** (9 points) (*Continuation of previous problem.*) Here are the Hoare rules for SKIP, THROW, assignment, and conditionals.

$$\{\! \{ P \} \!\} \text{ SKIP } \{\! \{ P \} \!\} \{\! \{ R \} \!\} \quad (\text{hoare_skip})$$

$$\{\! \{ P \} \!\} \text{ THROW } \{\! \{ Q \} \!\} \{\! \{ P \} \!\} \quad (\text{hoare_stop})$$

$$\frac{}{\{\! \{ \text{assn_sub } X \ a \ Q \} \!\} X := a \{\! \{ Q \} \!\} \{\! \{ R \} \!\}} \quad (\text{hoare_asgn})$$

$$\frac{\begin{array}{l} \{\! \{ P \wedge b \} \!\} c1 \{\! \{ Q \} \!\} \{\! \{ R \} \!\} \\ \{\! \{ P \wedge \sim b \} \!\} c2 \{\! \{ Q \} \!\} \{\! \{ R \} \!\} \end{array}}{\{\! \{ P \} \!\} \text{ IFB } b \text{ THEN } c1 \text{ ELSE } c2 \text{ FI } \{\! \{ Q \} \!\} \{\! \{ R \} \!\}} \quad (\text{hoare_if})$$

Write down appropriate rules for sequencing, TRY, and WHILE. (Just give the rules—no need to prove them!)

9. (9 points) The Fibonacci function can be defined as follows:

$$\text{fib}(n) = \begin{cases} 1 & \text{if } n = 0 \\ 1 & \text{if } n = 1 \\ \text{fib}(n-1) + \text{fib}(n-2) & \text{otherwise} \end{cases}$$

(Coq won't accept this as a definition because it will fail to pass the termination checker. It isn't very hard to reformulate it in a way that makes Coq happy, but we'll stick with this one here, since it's a bit easier to look at.) The first few Fibonacci numbers are: 1, 1, 2, 3, 5, 8, 13, ...

The following Imp program computes the n th Fibonacci number and leaves it in the variable Y .

```
X ::= 1;;
Y ::= 1;;
Z ::= 1;;
WHILE X <> n+1 DO
  T ::= Z;;
  Z ::= Z + Y;;
  Y ::= T;;
  X ::= X + 1
END
```

1. Explain, in English, the roles of the variables X , Y , Z , and T in this program.

2. Suppose we want to prove the Hoare triple $\{\{\text{True}\}\} \text{fibc} \{\{Y = \text{fib } n\}\}$, where fibc is the Imp program above.

Write down a suitable loop invariant for this proof.

10. **[Standard Only]** (10 points) On the next page, add appropriate annotations to the program in the provided spaces to show that the Hoare triple given by the outermost pre- and post-conditions is valid. Please be completely precise and pedantic in the way you apply the Hoare rules — i.e., write out assertions in *exactly* the form given by the rules (rather than logically equivalent ones). The provided blanks have been constructed so that, if you work backwards from the end of the program, you should only need to use the rule of consequence in the places indicated with `->>`.

The implication steps in your decoration may rely (silently) on all the usual rules of natural-number arithmetic. You may also assume the following equations about `fib`:

```
fib 0 = 1
fib 1 = 1
fib (n+2) = fib (n+1) + fib n
```

The rules of Hoare logic and the rules for well-formed decorated programs can be found on pages 3 and 4 of the handout.

```

{{ True }} ->>

{{
X ::= 1 ;;

{{
Y ::= 1 ;;

{{
Z ::= 1 ;;

{{
WHILE X <> n+1 DO

  {{
  }} ->>

  {{
  }}

  T ::= Z ;;

  {{
  }}

  Z ::= Z + Y ;;

  {{
  }}

  Y ::= T ;;

  {{
  }}

  X ::= X + 1 ;;

  {{
  }}

END

{{
  }} ->>

{{ Y = fib n }}

```

For Reference

Formal definitions for Imp

Syntax

```
Inductive aexp : Type := | ANum : nat -> aexp | AId : id -> aexp |
APlus : aexp -> aexp -> aexp | AMinus : aexp -> aexp -> aexp | AMult :
aexp -> aexp -> aexp.
```

```
Inductive bexp : Type :=
| BTrue : bexp
| BFalse : bexp
| BEq : aexp -> aexp -> bexp
| BLe : aexp -> aexp -> bexp
| BNot : bexp -> bexp
| BAnd : bexp -> bexp -> bexp.
```

```
Inductive com : Type :=
| CSkip : com
| CAss : id -> aexp -> com
| CSeq : com -> com -> com
| CIf : bexp -> com -> com -> com
| CWhile : bexp -> com -> com.
```

```
Notation "'SKIP'" :=
  CSkip.
```

```
Notation "l '::=' a" :=
  (CAss l a) (at level 60).
```

```
Notation "c1 ;; c2" :=
  (CSeq c1 c2) (at level 80, right associativity).
```

```
Notation "'WHILE' b 'DO' c 'END'" :=
  (CWhile b c) (at level 80, right associativity).
```

```
Notation "'IFB' e1 'THEN' e2 'ELSE' e3 'FI'" :=
  (CIf e1 e2 e3) (at level 80, right associativity).
```

Evaluation relation

```
Inductive ceval : com -> state -> state -> Prop :=
| E_Skip : forall st,
  SKIP / st \\ st
| E_Ass  : forall st a1 n X,
  aeval st a1 = n ->
  (X ::= a1) / st \\ (update st X n)
| E_Seq  : forall c1 c2 st st' st'',
  c1 / st \\ st' ->
  c2 / st' \\ st'' ->
  (c1 ;; c2) / st \\ st''
| E_IfTrue : forall st st' b1 c1 c2,
  beval st b1 = true ->
  c1 / st \\ st' ->
  (IFB b1 THEN c1 ELSE c2 FI) / st \\ st'
| E_IfFalse : forall st st' b1 c1 c2,
  beval st b1 = false ->
  c2 / st \\ st' ->
  (IFB b1 THEN c1 ELSE c2 FI) / st \\ st'
| E_WhileEnd : forall b1 st c1,
  beval st b1 = false ->
  (WHILE b1 DO c1 END) / st \\ st
| E_WhileLoop : forall st st' st'' b1 c1,
  beval st b1 = true ->
  c1 / st \\ st' ->
  (WHILE b1 DO c1 END) / st' \\ st'' ->
  (WHILE b1 DO c1 END) / st \\ st''

where "c1 '/' st '\\ st'" := (ceval c1 st st').
```

Program equivalence

```
Definition bequiv (b1 b2 : bexp) : Prop :=
  forall (st:state), beval st b1 = beval st b2.
```

```
Definition cequiv (c1 c2 : com) : Prop :=
  forall (st st' : state),
  (c1 / st \\ st') <-> (c2 / st \\ st').
```

Hoare triples

```
Definition hoare_triple (P:Assertion) (c:com) (Q:Assertion) : Prop :=
  forall st st', c / st \\ st' -> P st -> Q st'.
```

```
Notation "{ P } c { Q }" := (hoare_triple P c Q).
```

Implication on assertions

Definition `assert_implies (P Q : Assertion) : Prop := forall st, P st -> Q st.`

Notation "`P ->> Q`" := (`assert_implies P Q`) (at level 80).

(ASCII `->>` is typeset as a hollow arrow in the rules below.)

Hoare logic rules

$$\frac{}{\{\text{assn_sub } X \ a \ Q\} X := a \ \{\!Q\}} \text{ (hoare_asgn)}$$

$$\frac{}{\{P\} \text{ SKIP } \{P\}} \text{ (hoare_skip)}$$

$$\frac{\{P\} \ c1 \ \{Q\} \quad \{Q\} \ c2 \ \{R\}}{\{P\} \ c1;; \ c2 \ \{R\}} \text{ (hoare_seq)}$$

$$\frac{\{P \wedge b\} \ c1 \ \{Q\} \quad \{P \wedge \sim b\} \ c2 \ \{Q\}}{\{P\} \ \text{IFB } b \ \text{THEN } c1 \ \text{ELSE } c2 \ \text{FI } \{Q\}} \text{ (hoare_if)}$$

$$\frac{\{P \wedge b\} \ c \ \{P\}}{\{P\} \ \text{WHILE } b \ \text{DO } c \ \text{END } \{P \wedge \sim b\}} \text{ (hoare_while)}$$

$$\frac{\{P'\} \ c \ \{Q'\} \quad P \rightarrow P' \quad Q' \rightarrow Q}{\{P\} \ c \ \{Q\}} \text{ (hoare_consequence)}$$

$$\frac{\{P'\} \ c \ \{Q\} \quad P \rightarrow P'}{\{P\} \ c \ \{Q\}} \text{ (hoare_consequence_pre)}$$

$$\frac{\{P\} \ c \ \{Q'\} \quad Q' \rightarrow Q}{\{P\} \ c \ \{Q\}} \text{ (hoare_consequence_post)}$$

Decorated programs

1. SKIP is locally consistent if its precondition and postcondition are the same:

```
  {{ P }}
  SKIP
  {{ P }}
```

2. The sequential composition of $c1$ and $c2$ is locally consistent (with respect to assertions P and R) if $c1$ is locally consistent (with respect to P and Q) and $c2$ is locally consistent (with respect to Q and R):

```
  {{ P }}
  c1;
  {{ Q }}
  c2
  {{ R }}
```

3. An assignment is locally consistent if its precondition is the appropriate substitution of its postcondition:

```
  {{ P [X |-> a] }}
  X ::= a
  {{ P }}
```

4. A conditional is locally consistent (with respect to assertions P and Q) if the assertions at the top of its "then" and "else" branches are exactly $P \wedge b$ and $P \wedge \sim b$ and if its "then" branch is locally consistent (with respect to $P \wedge b$ and Q) and its "else" branch is locally consistent (with respect to $P \wedge \sim b$ and Q):

```
  {{ P }}
  IFB b THEN
    {{ P /\ b }}
    c1
    {{ Q }}
  ELSE
    {{ P /\ ~b }}
    c2
    {{ Q }}
  FI
  {{ Q }}
```

5. A while loop with precondition P is locally consistent if its postcondition is $P \wedge \sim b$ and if the pre- and postconditions of its body are exactly $P \wedge b$ and P :

```

    {{ P }}
  WHILE b DO
    {{ P /\ b }}
    c1
    {{ P }}
  END
  {{ P /\ ~b }}

```

6. A pair of assertions separated by \rightarrow is locally consistent if the first implies the second (in all states):

```

  {{ P }}  $\rightarrow$ 
  {{ P' }}

```

Relations

Definition `relation (X: Type) := X->X->Prop.`

```

Inductive multi {X:Type} (R: relation X) : relation X :=
| multi_refl  : forall (x : X), multi R x x
| multi_step  : forall (x y z : X),
    R x y ->
    multi R y z ->
    multi R x z.

```

Notation "`t '==>' t'`" := `(multi step t t')` (at level 40).

Small Step Semantics

Reserved Notation "`t '/' st '==>a' t'`" (at level 40, `st` at level 39).

```

Inductive astep : state -> aexp -> aexp -> Prop :=
| AS_Id : forall st i,
  AId i / st ==>a ANum (st i)
| AS_Plus : forall st n1 n2,
  APlus (ANum n1) (ANum n2) / st ==>a ANum (n1 + n2)
| AS_Plus1 : forall st a1 a1' a2,
  a1 / st ==>a a1' ->
  (APlus a1 a2) / st ==>a (APlus a1' a2)
| AS_Plus2 : forall st v1 a2 a2',
  aval v1 ->
  a2 / st ==>a a2' ->
  (APlus v1 a2) / st ==>a (APlus v1 a2')
| AS_Minus : forall st n1 n2,

```

```

      (AMinus (ANum n1) (ANum n2)) / st ==>a (ANum (minus n1 n2))
| AS_Minus1 : forall st a1 a1' a2,
  a1 / st ==>a a1' ->
  (AMinus a1 a2) / st ==>a (AMinus a1' a2)
| AS_Minus2 : forall st v1 a2 a2',
  aval v1 ->
  a2 / st ==>a a2' ->
  (AMinus v1 a2) / st ==>a (AMinus v1 a2')
| AS_Mult : forall st n1 n2,
  (AMult (ANum n1) (ANum n2)) / st ==>a (ANum (mult n1 n2))
| AS_Mult1 : forall st a1 a1' a2,
  a1 / st ==>a a1' ->
  (AMult a1 a2) / st ==>a (AMult a1' a2)
| AS_Mult2 : forall st v1 a2 a2',
  aval v1 ->
  a2 / st ==>a a2' ->
  (AMult v1 a2) / st ==>a (AMult v1 a2')
where " t '/' st '==>a' t' " := (astep st t t').

```

Reserved Notation " t '/' st '==>' t' '/' st' "
 (at level 40, st at level 39, t' at level 39).

```

Inductive cstep : (com * state) -> (com * state) -> Prop :=
| CS_AssStep : forall st i a a',
  a / st ==>a a' ->
  (i ::= a) / st ==> (i ::= a') / st
| CS_Ass : forall st i n,
  (i ::= (ANum n)) / st ==> SKIP / (t_update st i n)
| CS_SeqStep : forall st c1 c1' st' c2,
  c1 / st ==> c1' / st' ->
  (c1 ;; c2) / st ==> (c1' ;; c2) / st'
| CS_SeqFinish : forall st c2,
  (SKIP ;; c2) / st ==> c2 / st
| CS_IfTrue : forall st c1 c2,
  IFB BTrue THEN c1 ELSE c2 FI / st ==> c1 / st
| CS_IfFalse : forall st c1 c2,
  IFB BFalse THEN c1 ELSE c2 FI / st ==> c2 / st
| CS_IfStep : forall st b b' c1 c2,
  b / st ==>b b' ->
  IFB b THEN c1 ELSE c2 FI / st
  ==> (IFB b' THEN c1 ELSE c2 FI) / st
| CS_While : forall st b c1,
  (WHILE b DO c1 END) / st
  ==> (IFB b THEN (c1;; (WHILE b DO c1 END)) ELSE SKIP FI) / st
where " t '/' st '==>' t' '/' st' " := (cstep (t,st) (t',st')).

```