



软件理论基础与实践

Imp: Simple Imperative Programs

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课程进展

- Coq ✓
- 数理逻辑基础 ✓
- 形式语义
- 类型系统



高可信软件验证

- Coq要求递归为（Coq能分析出来的）结构递归
- 大量程序根本无法用Coq写出
- 如何采用Coq进行高可信软件验证？
- 首先在Coq中定义出一个程序设计语言
 - 该语言的程序是符合某种自定义类型的数据，不受Coq递归的限制
 - 需要定义语法
- 然后论证该语言对应程序的性质
 - 需要定义语义



本次课目标

- 定义一个命令式程序设计语言IMP

```
Z := X;  
    Y := 1;  
    while ~(Z = 0) do  
        Y := Y × Z;  
        Z := Z - 1  
    end
```

- 先从定义语言的表达式开始



定义语法

- 语法定义通常采用上下文无关文法并写作BNF形式

```
a := nat
   | a + a
   | a - a
   | a × a

b := true
   | false
   | a = a
   | a ≤ a
   | ¬b
   | b && b
```



定义语法

- 上下文无关文法记录为Coq的归纳定义

```
a := nat
| a + a
| a - a
| a × a

b := true
| false
| a = a
| a ≤ a
| ¬b
| b && b
```

```
Inductive aexp : Type :=
| ANum (n : nat)
| APlus (a1 a2 : aexp)
| AMinus (a1 a2 : aexp)
| AMult (a1 a2 : aexp).
```

```
Inductive bexp : Type :=
| BTrue
| BFalse
| BEq (a1 a2 : aexp)
| BLe (a1 a2 : aexp)
| BNot (b : bexp)
| BAnd (b1 b2 : bexp).
```



形式语义

- 操作语义
 - 将程序元素解释为计算步骤
- 指称语义
 - 将程序元素解释为数学中严格定义的对象，通常为函数
- 操作语义 vs 指称语义
 - 在现代程序语义学的教材中，二者通常是等价的，只是惯用符号不同
 - 操作语义常采用逻辑推导规则描述，指称语义常采用集合定义描述
 - 本书采用集合定义的方式描述了自称为操作语义的语义
- 公理语义
 - 将程序元素解释为前条件和后条件，并可用霍尔逻辑推导
 - 将在《Programming Language Foundations》部分介绍



语义建模成函数

```
Fixpoint aeval (a : aexp) : nat :=  
  match a with  
  | ANum n => n  
  | APlus a1 a2 => (aeval a1) + (aeval a2)  
  | AMinus a1 a2 => (aeval a1) - (aeval a2)  
  | AMult a1 a2 => (aeval a1) * (aeval a2)  
  end.
```

```
Fixpoint beval (b : bexp) : bool :=  
  match b with  
  | BTrue      => true  
  | BFalse     => false  
  | BEq a1 a2  => (aeval a1) =? (aeval a2)  
  | BLe a1 a2  => (aeval a1) <=? (aeval a2)  
  | BNot b1    => negb (beval b1)  
  | BAnd b1 b2 => andb (beval b1) (beval b2)  
  end.
```




优化是从程序到程序的映射

```
Fixpoint optimize_0plus (a:aexp) : aexp :=  
  match a with  
  | ANum n => ANum n  
  | APlus (ANum 0) e2 => optimize_0plus e2  
  | APlus e1 e2 => APlus (optimize_0plus e1) (optimize_0plus e2)  
  | AMinus e1 e2 => AMinus (optimize_0plus e1) (optimize_0plus e2)  
  | AMult e1 e2 => AMult (optimize_0plus e1) (optimize_0plus e2)  
end.
```



优化的正确性

Theorem `optimize_0plus_sound`: `forall` a,
aeval (optimize_0plus a) = aeval a.

Proof.

`intros a. induction a.`

- `(* ANum *) reflexivity.`
- `(* APlus *) destruct a1 eqn:Ea1.`
 - + `(* a1 = ANum n *) destruct n eqn:En.`
 - * `(* n = 0 *) simpl. apply IHa2.`
 - * `(* n <> 0 *) simpl. rewrite IHa2. reflexivity.`
 - + `(* a1 = APlus a1_1 a1_2 *)`
`simpl. simpl in IHa1. rewrite IHa1. rewrite IHa2. reflexivity.`
 - + `(* a1 = AMinus a1_1 a1_2 *)`
`simpl. simpl in IHa1. rewrite IHa1. rewrite IHa2. reflexivity.`
 - + `(* a1 = AMult a1_1 a1_2 *)`
`simpl. simpl in IHa1. rewrite IHa1. rewrite IHa2. reflexivity.`
- `(* AMinus *)`
`simpl. rewrite IHa1. rewrite IHa2. reflexivity.`
- `(* AMult *)`
`1simpl. rewrite IHa1. rewrite IHa2. reflexivity. Qed.`



优化的正确性

Theorem `optimize_0plus_sound`: `forall a,`
`aeval (optimize_0plus a) = aeval a.`

Proof.

`intros a. induction a.`

- `(* ANum *) reflexivity.`

- `(* APlus *) destruct a1 eqn:Ea1.`

+ `(* a1 = ANum n *) destruct n eqn:En.`

+ `(* n = 0 *) simpl. apply IHa2.`

+ `(*`

+ `(* a1 = ANum n1 a1_1 a1_2 *)`
`simpl. reflexivity.`

+ `(* a1 = ANum n1 a1_1 a1_2 *)`
`simpl. simpl in IHa1. rewrite IHa1. rewrite IHa2. reflexivity.`

+ `(* a1 = AMult a1_1 a1_2 *)`
`simpl. simpl in IHa1. rewrite IHa1. rewrite IHa2. reflexivity.`

- `(* AMinus *)`
`simpl. rewrite IHa1. rewrite IHa2. reflexivity.`

- `(* AMult *)`
`simpl. rewrite IHa1. rewrite IHa2. reflexivity. Qed.`

需要减少定理证明中的重复



try策略

```
Theorem silly1 : forall ae, aeval ae = aeval ae.  
Proof. try reflexivity. (* This just does [reflexivity]. *) Qed.  
  
Theorem silly2 : forall (P : Prop), P -> P.  
Proof.  
  intros P HP.  
  try reflexivity. (* Just [reflexivity] would have failed. *)  
  apply HP. (* We can still finish the proof in some other way. *)  
Qed.
```

try T会应用T，如果T失败，就当什么都没发生



分号策略

T;T'首先应用T，然后将T'应用到所有T产生的子目标上。

```
Lemma foo : forall n, 0 <=? n = true.  
Proof.  
  intros.  
  destruct n.  
  - (* n=0 *) simpl. reflexivity.  
  - (* n=S n' *) simpl. reflexivity.  
Qed.
```

```
Lemma foo' : forall n, 0 <=? n = true.  
Proof.  
  intros.  
  destruct n;  
  simpl;  
  reflexivity.  
Qed.
```



用分号策略改写证明

```
Theorem optimize_0plus_sound': forall a,  
  aeval (optimize_0plus a) = aeval a.
```

Proof.

```
  intros a.
```

```
  induction a;
```

```
    (* Most cases follow directly by the IH *)
```

```
    try (simpl; rewrite IHa1; rewrite IHa2; reflexivity);
```

```
    (* ... or are immediate by definition *)
```

```
    try reflexivity.
```

```
  (* The interesting case is when a = APlus a1 a2. *)
```

```
  - (* APlus *)
```

```
    destruct a1; try (simpl; simpl in IHa1; rewrite IHa1;  
                      rewrite IHa2; reflexivity).
```

```
  + (* a1 = ANum n *) destruct n;
```

```
    simpl; rewrite IHa2; reflexivity. Qed.
```



分号策略的通用形式

- $T; [T1 \mid T2 \mid \dots \mid Tn]$
 - 首先应用 T ，然后把 $T1..Tn$ 分别应用到 T 生成的子目标上
- $T;T'$ 是 $T; [T' \mid T' \mid \dots \mid T']$ 的简写形式



repeat策略

repeat T反复应用T直到失败

```
Theorem In10 : In 10 [1;2;3;4;5;6;7;8;9;10].  
Proof.  
  repeat (try (left; reflexivity); right).  
Qed.
```

```
Theorem repeat_loop : forall (m n : nat),  
  m + n = n + m.  
Proof.  
  intros m n.  
  repeat rewrite Nat.add_comm.  
  (* 死机 *)
```




定义简单的策略

- 用Tactic Notation可以定义简单的策略

```
Tactic Notation "simpl_and_try" tactic(c) :=  
  simpl;  
  try c.
```

- 更复杂的策略可以用Ltac定义，本课程不涉及



lia策略

- 可用于快速证明线性表达式定理

```
Example silly_presburger_example : forall m n o p,  
  m + n <= n + o /\ o + 3 = p + 3 ->  
  m <= p.  
Proof.  
  intros. lia.  
Qed.
```

```
Example plus_comm__omega : forall m n,  
  m + n = n + m.  
Proof.  
  intros. lia.  
Qed.
```

- 如果原命题无法被证明或证明失败（无法区分二者），则策略应用失败



其他一些策略

- `clear H`: 删除假设H
- `subst x`: 如果存在 $x=e$ 或者 $e=x$ 的假设，则删除该假设并把x替换成e
- `subst`: 对所有变量应用上述策略
- `rename... into...`: 对变量/假设改名
- `assumption`: 寻找和目标一样的假设并应用
- `contradiction`: 寻找和False等价的假设并推出矛盾
- `constructor`: 寻找一个可以匹配目标的归纳定义构造函数c，并执行`apply c`。



语义建模成函数的问题

- Coq中的函数必须是全函数

```
Inductive aexp : Type :=  
  | ANum (n : nat)  
  | APlus (a1 a2 : aexp)  
  | AMinus (a1 a2 : aexp)  
  | AMult (a1 a2 : aexp)  
  | ADiv (a1 a2 : aexp).
```

```
Inductive aexp : Type :=  
  | AAny (* 产生随机数 *)  
  | ANum (n : nat)  
  | APlus (a1 a2 : aexp)  
  | AMinus (a1 a2 : aexp)  
  | AMult (a1 a2 : aexp).
```

- Coq中的函数必须在Coq编译器的分析能力内能终止
 - while(true);
 - while($n^5 + n = 34$) n++;



语义建模成关系

```
Inductive aevalR : aexp -> nat -> Prop :=
| E_ANum (n : nat) :
  aevalR (ANum n) n
| E_APlus (e1 e2 : aexp) (n1 n2 : nat) :
  aevalR e1 n1 ->
  aevalR e2 n2 ->
  aevalR (APlus e1 e2) (n1 + n2)
| E_AMinus (e1 e2 : aexp) (n1 n2 : nat) :
  aevalR e1 n1 ->
  aevalR e2 n2 ->
  aevalR (AMinus e1 e2) (n1 - n2)
| E_AMult (e1 e2 : aexp) (n1 n2 : nat) :
  aevalR e1 n1 ->
  aevalR e2 n2 ->
  aevalR (AMult e1 e2) (n1 * n2).
```



语义建模

先保留符号，就可以在定义过程中递归使用

Reserved Notation "e '==>' n" (at level 90, left associativity).

```
Inductive aevalR : aexp -> nat -> Prop :=
| E_ANum (n : nat) :
  (ANum n) ==> n
| E_APlus (e1 e2 : aexp) (n1 n2 : nat) :
  (e1 ==> n1) -> (e2 ==> n2) -> (APlus e1 e2) ==> (n1 + n2)
| E_AMinus (e1 e2 : aexp) (n1 n2 : nat) :
  (e1 ==> n1) -> (e2 ==> n2) -> (AMinus e1 e2) ==> (n1 - n2)
| E_AMult (e1 e2 : aexp) (n1 n2 : nat) :
  (e1 ==> n1) -> (e2 ==> n2) -> (AMult e1 e2) ==> (n1 * n2)
| E_ADiv (a1 a2 : aexp) (n1 n2 n3 : nat) :
  (a1 ==> n1) -> (a2 ==> n2) -> (n2 > 0) ->
  (mult n2 n3 = n1) -> (ADiv a1 a2) ==> n3

where "e '==>' n" := (aevalR e n) : type_scope.
```

语义建模成关系（推导规则）



$$\overline{\text{ANum } n \Rightarrow n}$$

$$\frac{\begin{array}{l} e_1 \Rightarrow n_1 \\ e_2 \Rightarrow n_2 \end{array}}{\text{APlus } e_1 \ e_2 \Rightarrow n_1 + n_2}$$

$$\frac{\begin{array}{l} e_1 \Rightarrow n_1 \\ e_2 \Rightarrow n_2 \end{array}}{\text{AMinus } e_1 \ e_2 \Rightarrow n_1 - n_2}$$

$$\frac{\begin{array}{l} e_1 \Rightarrow n_1 \\ e_2 \Rightarrow n_2 \end{array}}{\text{AMult } e_1 \ e_2 \Rightarrow n_1 * n_2}$$

$$\frac{\begin{array}{l} e_1 \Rightarrow n_1 \quad e_2 \Rightarrow n_2 \\ n_2 * n_3 = n_1 \quad n_2 > 0 \end{array}}{\text{ADiv } e_1 \ e_2 \Rightarrow n_3}$$



关系 vs 函数

- 建模成关系更自由，有时也更方便
 - 本身就不是函数
 - 较难在Coq中建模成函数
 - Coq自动生成的归纳定理会让一些证明更方便
- 建模成函数通常更方便
 - 前提可以直接计算验证，而非关系
 - 支持simpl
 - 函数还可以用在构造类型中



带变量的表达式

```
Definition state := total_map nat.
```

```
Inductive aexp : Type :=  
  | ANum (n : nat)  
  | AId (x : string)  
  | APlus (a1 a2 : aexp)  
  | AMinus (a1 a2 : aexp)  
  | AMult (a1 a2 : aexp).
```



解析表达式

```
Definition W : string := "W".  
Definition X : string := "X".  
Definition Y : string := "Y".  
Definition Z : string := "Z".
```

声明隐式转换

```
Coercion AId : string >-> aexp.  
Coercion ANum : nat >-> aexp.
```

创建专用语法com

```
Declare Custom Entry com.  
Declare Scope com_scope.
```

```
Notation "<{ e }>" := e  
  (at level 0, e custom com at level 99) : com_scope.
```

<{ }>中的表达式用
专用语法解析



解析表达式

```
Notation "( x )" := x (in custom com, x at level 99) : com_scope.
Notation "x" := x (in custom com at level 0, x constr at level 0) : com_scope.
Notation "f x .. y" := (.. (f x) .. y)
                        (in custom com at level 0, only parsing,
                        f constr at level 0, x constr at level 9,
                        y constr at level 9) : com_scope.
Notation "x + y" := (APlus x y) (in custom com at level 50, left associativity).
Notation "x - y" := (AMinus x y) (in custom com at level 50, left associativity).
Notation "x * y" := (AMult x y) (in custom com at level 40, left associativity).
Notation "'true'" := true (at level 1).
Notation "'true'" := BTrue (in custom com at level 0).
Notation "'false'" := false (at level 1).
Notation "'false'" := BFalse (in custom com at level 0).
Notation "x <= y" := (BLe x y) (in custom com at level 70, no associativity).
Notation "x = y" := (BEq x y) (in custom com at level 70, no associativity).
Notation "x && y" := (BAnd x y) (in custom com at level 80, left associativity).
Notation "'~' b" := (BNot b) (in custom com at level 75, right associativity).

Open Scope com_scope.
```



解析表达式

Definition `example_aexp` : `aexp` := `<{ 3 + (X * 2) }>`.

Definition `example_bexp` : `bexp` := `<{ true && ~(X <= 4) }>`.



修改语义函数

```
Fixpoint aeval (st : state) (a : aexp) : nat :=  
  match a with  
  | ANum n => n  
  | AId x => st x (* <--- 新增 *)  
  | <{a1 + a2}> => (aeval st a1) + (aeval st a2)  
  | <{a1 - a2}> => (aeval st a1) - (aeval st a2)  
  | <{a1 * a2}> => (aeval st a1) * (aeval st a2)  
  end.
```

```
Fixpoint beval (st : state) (b : bexp) : bool :=  
  match b with  
  | <{true}>      => true  
  | <{false}>     => false  
  | <{a1 = a2}>   => (aeval st a1) =? (aeval st a2)  
  | <{a1 <= a2}>  => (aeval st a1) <=? (aeval st a2)  
  | <{~ b1}>      => negb (beval st b1)  
  | <{b1 && b2}>  => andb (beval st b1) (beval st b2)  
  end.
```



程序示例

```
Definition empty_st := (_ !-> 0).
```

```
Notation "x '!->' v" := (t_update empty_st x v) (at level 100).
```

```
Example aexp1 :  
  aeval (X !-> 5) <{ (3 + (X * 2)) }>  
  = 13.
```

```
Proof. reflexivity. Qed.
```

```
Example bexp1 :  
  beval (X !-> 5) <{ true && ~(X <= 4) }>  
  = true.
```

```
Proof. reflexivity. Qed.
```



IMP顶层语法

```
c := skip
| x := a
| c ; c
| if b then c else c end
| while b do c end
```

```
Inductive com : Type :=
| CSkip
| CAss (x : string) (a : aexp)
| CSeq (c1 c2 : com)
| CIf (b : bexp) (c1 c2 : com)
| CWhile (b : bexp) (c : com).
```



解析程序

```
Notation "'skip'" :=
  CSkip (in custom com at level 0) : com_scope.
Notation "x := y" :=
  (CAss x y)
  (in custom com at level 0, x constr at level 0,
   y at level 85, no associativity) : com_scope.
Notation "x ; y" :=
  (CSeq x y)
  (in custom com at level 90, right associativity) : com_scope.
Notation "'if' x 'then' y 'else' z 'end'" :=
  (CIf x y z)
  (in custom com at level 89, x at level 99,
   y at level 99, z at level 99) : com_scope.
Notation "'while' x 'do' y 'end'" :=
  (CWhile x y)
  (in custom com at level 89, x at level 99,
   y at level 99) : com_scope.
```




程序示例

```
Definition fact_in_coq : com :=
```

```
<{ Z := X;  
  Y := 1;  
  while ~(Z = 0) do  
    Y := Y * Z;  
    Z := Z - 1  
  end }>.
```

```
Print fact_in_coq.
```

```
(* fact_in_coq =  
<{ Z := X; Y := 1; while ~ Z = 0 do Y := Y * Z; Z := Z - 1 end }>  
: com *)
```



控制打印内容

```
Unset Printing Notations.
```

```
Print fact_in_coq.
```

```
(* ==>  
  fact_in_coq =  
    CSeq (CAss Z X)  
      (CSeq (CAss Y (S 0))  
        (CWhile (BNot (BEq Z 0))  
          (CSeq (CAss Y (AMult Y Z))  
            (CAss Z (AMinus Z (S 0)))))))  
      : com *)
```

```
Set Printing Notations.
```



控制打印内容

```
Set Printing Coercions.  
Print fact_in_coq.  
(* ==>  
  fact_in_coq =  
  <{ Z := (AId X);  
    Y := (ANum 1);  
    while ~ (AId Z) = (ANum 0) do  
      Y := (AId Y) * (AId Z);  
      Z := (AId Z) - (ANum 1)  
    end }>  
    : com *)  
Unset Printing Coercions.
```



Locate命令

- 之前学过Search命令用于查找符合条件的定义或定理，输出名字和类型
- Locate命令用于给出一个符号的完整名称或者Notation定义

```
Locate "&&".  
(* ==>  
    Notation  
    "x && y" := BAnd x y (default interpretation)  
    "x && y" := andb x y : bool_scope (default interpretation)  
*)
```



Locate命令

```
Locate "while".  
(* ==>  
    Notation  
    "'while' x 'do' y 'end'" :=  
        CWhile x y : com_scope (default interpretation)  
    "'_' '!-->' v" := t_empty v (default interpretation)  
*)
```



Locate命令

```
Locate aexp.  
(* ==>  
    Inductive LF.Imp.aexp  
    Inductive LF.Imp.AExp.aexp  
        (shorter name to refer to it in current context  
         is AExp.aexp)  
    Inductive LF.Imp.aevalR_division.aexp  
        (shorter name to refer to it in current context  
         is aevalR_division.aexp)  
    Inductive LF.Imp.aevalR_extended.aexp  
        (shorter name to refer to it in current context  
         is aevalR_extended.aexp)  
*)
```



命令的语义

$$\frac{}{st = [skip] \Rightarrow st} \text{ (E_Skip)}$$

$$\frac{aeval \ st \ a = n}{st = [x := a] \Rightarrow (x \mapsto n ; st)} \text{ (E_Ass)}$$

$$\frac{\begin{array}{l} st = [c_1] \Rightarrow st' \\ st' = [c_2] \Rightarrow st'' \end{array}}{st = [c_1 ; c_2] \Rightarrow st''} \text{ (E_Seq)}$$

$$\frac{\begin{array}{l} beval \ st \ b = true \\ st = [c_1] \Rightarrow st' \end{array}}{st = [\text{if } b \text{ then } c_1 \text{ else } c_2 \text{ end}] \Rightarrow st'} \text{ (E_IfTrue)}$$



命令的语义

$$\frac{\begin{array}{l} \text{beval } st \ b = \text{false} \\ st = [c_2] \Rightarrow st' \end{array}}{st = [\text{if } b \text{ then } c_1 \text{ else } c_2 \text{ end}] \Rightarrow st'} \quad (\text{E_IfFalse})$$

$$\frac{\text{beval } st \ b = \text{false}}{st = [\text{while } b \text{ do } c \text{ end}] \Rightarrow st} \quad (\text{E_WhileFalse})$$

$$\frac{\begin{array}{l} \text{beval } st \ b = \text{true} \\ st = [c] \Rightarrow st' \\ st' = [\text{while } b \text{ do } c \text{ end}] \Rightarrow st'' \end{array}}{st = [\text{while } b \text{ do } c \text{ end}] \Rightarrow st''} \quad (\text{E_WhileTrue})$$



对应Coq关系

Reserved Notation

`"st '=[' c ']=> ' st'"`

(at level 40, c custom com at level 99,
st constr, st' constr at next level).

Inductive `ceval` : com -> state -> state -> Prop :=

```
| E_Skip : forall st,  
  st =[ skip ]=> st  
| E_Ass   : forall st a n x,  
  aeval st a = n ->  
  st =[ x := a ]=> (x !-> n ; st)  
| E_Seq   : forall c1 c2 st st' st'',  
  st  =[ c1 ]=> st' ->  
  st' =[ c2 ]=> st'' ->  
  st  =[ c1 ; c2 ]=> st''
```



对应Coq关系

```
| E_IfTrue : forall st st' b c1 c2,  
  beval st b = true ->  
  st =[ c1 ]=> st' ->  
  st =[ if b then c1 else c2 end ]=> st'  
| E_IfFalse : forall st st' b c1 c2,  
  beval st b = false ->  
  st =[ c2 ]=> st' ->  
  st =[ if b then c1 else c2 end ]=> st'  
| E_WhileFalse : forall b st c,  
  beval st b = false ->  
  st =[ while b do c end ]=> st  
| E_WhileTrue : forall st st' st'' b c,  
  beval st b = true ->  
  st  =[ c ]=> st' ->  
  st' =[ while b do c end ]=> st'' ->  
  st  =[ while b do c end ]=> st''  
  
where "st =[ c ]=> st'" := (ceval c st st').
```



程序运行举例

```
Example ceval_example1:
  empty_st = [
    X := 2;
    if (X <= 1)
      then Y := 3
      else Z := 4
    end
  ] => (Z !-> 4 ; X !-> 2).
```

Proof.

```
apply E_Seq with (X !-> 2).
- (* assignment command *)
  apply E_Ass. reflexivity.
- (* if command *)
  apply E_IfFalse.
  reflexivity.
  apply E_Ass. reflexivity.
```

Qed.



定理证明举例

```
Definition plus2 : com :=  
  <{ X := X + 2 }>.
```

```
Theorem plus2_spec : forall st n st',  
  st X = n ->  
  st =[ plus2 ]=> st' ->  
  st' X = n + 2.
```

```
Lemma t_update_eq : forall (A : Type) (m : total_map A) x v,  
  (x !-> v ; m) x = v.
```

证明会用到t_update_eq，是在Maps一章证明的引理



定理证明举例

Proof.

```
  intros st n st' HX Heval.
(** [Coq Proof View]
 * 1 subgoal
 *
 *   st : string -> nat
 *   n : nat
 *   st' : state
 *   HX : st X = n
 *   Heval : st =[ plus2 ]=> st'
 *   =====
 *   st' X = n + 2
 *)
```



定理证明举例

```
inversion Heval.
(** [Coq Proof View]
 * 1 subgoal
 *
 *   st : string -> nat
 *   n : nat
 *   st' : state
 *   HX : st X = n
 *   Heval : st =[ plus2 ]=> st'
 *   st0 : state
 *   a : aexp
 *   n0 : nat
 *   x : string
 *   H3 : aeval st <{ X + 2 }> = n0
 *   H : x = X
 *   H1 : a = <{ X + 2 }>
 *   H0 : st0 = st
 *   H2 : (X !-> n0; st) = st'
 *   =====
 *   (X !-> n0; st) X = n + 2
 *)
```



定理证明举例

```
subst.  
(** [Coq Proof View]  
* 1 subgoal  
*  
*   st : string -> nat  
*   Heval : st =[ plus2 ]=> (X !-> aeval st <{ X + 2 }>; st)  
*   =====  
*   (X !-> aeval st <{ X + 2 }>; st) X = st X + 2  
*)
```



定理证明举例

```
clear Heval.  
(** [Coq Proof View]  
* 1 subgoal  
*  
*   st : string -> nat  
*   =====  
*   (X !-> aeval st <{ X + 2 }>; st) X = st X + 2  
*)
```




定理证明举例

```
simpl.  
(** [Coq Proof View]  
* 1 subgoal  
*  
*   st : string -> nat  
*   =====  
*   (X !-> st X + 2; st) X = st X + 2  
*)  
  apply t_update_eq.  
(** No more subgoals. *)  
Qed.
```



作业

- 完成Imp中standard非optional并不属于Additional Exercises的6道习题
 - 请使用最新英文版教材
 - 从本章起证明长度有显著增加，请尽早动手