软件科学基础

Tactics: More Tactics

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apply策略

- apply策略直接应用假设完成结论推导

```
Theorem silly1 : forall (n m : nat),
  n = m ->
  n = m.
Proof. intros n m eq.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   eq : n = m
 *   ==========
 *   n = m
 *)
apply eq.(** No more subgoals. *)
Qed.
```

apply策略

- apply也可应用P->Q形式的假设把结论从Q变成P

```
Theorem silly2 : forall (n m o p : nat),
  n = m ->
  (n = m -> [n;o] = [m;p]) ->
  [n;o] = [m;p].
Proof. intros n m o p eq1 eq2.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m, o, p : nat
 *   eq1 : n = m
 *   eq2 : n = m -> [n; o] = [m; p]
 *   ==============================
 *   [n; o] = [m; p]
 *)
```

apply策略

- apply也可应用P->Q形式的假设把结论从Q变成P

```
 apply eq2.(** [Rocq Proof View]
* 1 subgoal
*
*   n, m, o, p : nat
*   eq1 : n = m
*   eq2 : n = m -> [n; o] = [m; p]
*   ==============================
*   n = m
*)
apply eq1.(** No more subgoals. *)
 Qed.
```

apply策略

- apply策略会自动替换全称量词

```
Theorem silly2a : forall (n m : nat),
  (n,n) = (m,m)  ->
  (forall (q r : nat), (q,q) = (r,r) -> [q] = [r]) ->
  [n] = [m].
Proof. intros n m eq1 eq2.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   eq1 : (n, n) = (m, m)
 *   eq2 : forall q r : nat, (q, q) = (r, r) -> [q] = [r]
 *   ========================================
 *   [n] = [m]
 *)
```

apply策略

- apply策略会自动替换全称量词

```
 apply eq2.(** [Rocq Proof View]
* 1 subgoal
*
*   n, m : nat
*   eq1 : (n, n) = (m, m)
*   eq2 : forall q r : nat, (q, q) = (r, r) -> [q] = [r]
*   ====================================================
*   (n, n) = (m, m)
*)
apply eq1.(** No more subgoals. *)
 Qed.
```

apply策略

- apply策略应用时假设和结论必须能完全匹配

```
Theorem silly3 : forall (n m : nat),
  n = m ->
  m = n.
Proof. intros n m H.
(**   H : n = m
 *   ==========
 *   m = n
 *)
  Fail apply H.
(** [Rocq Proof View]
 * The command has indeed failed with message:
 * In environment
 * n, m : nat
 * H : n = m
 * Unable to unify "n = m" with "m = n".
 *)
```

symmetry策略

- symmetry策略用于交换目标等式的左右两边

```
  symmetry.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   H : n = m
 *   ==========
 *   n = m
 *)
 apply H.(** No more subgoals. *)
  Qed.
```

apply with策略

- 如果定理前提中有自由变量，apply策略会失败

```
Theorem trans_eq : forall (X:Type) (x y z : X),
  x = y -> y = z -> x = z.
Proof.
  intros X x y z eq1 eq2. rewrite -> eq1. rewrite -> eq2.
  reflexivity.  Qed.

Example trans_eq_example' : forall (a b c d e f : nat),
     [a;b] = [c;d] ->
     [c;d] = [e;f] ->
     [a;b] = [e;f].
```

apply with策略

```
Proof.
  intros a b c d e f eq1 eq2.
(* a, b, c, d, e, f: nat
   eq1: [a; b] = [c; d]
   eq2: [c; d] = [e; f]
   ======================
   [a; b] = [e; f]
*)
  Fail apply trans_eq.
(* Unable to find an instance for the variable m. *)
```

apply with策略

- apply with指定自由变量的值

```
   apply trans_eq with (y:=[c;d]).
 (** [Rocq Proof View]
  * 2 subgoals
  *
  *   a, b, c, d, e, f : nat
  *   eq1 : [a; b] = [c; d]
  *   eq2 : [c; d] = [e; f]
  *   ======================
  *   [a; b] = [c; d]
  *
  * subgoal 2 is:
  *  [c; d] = [e; f]
  *)
   apply eq1. apply eq2.   Qed.
```

transitivity策略

- transitivity o等价于apply trans_eq with (y:=o)

```
Example trans_eq_example'' : forall (a b c d e f : nat),
     [a;b] = [c;d] ->
     [c;d] = [e;f] ->
     [a;b] = [e;f].
Proof.
  intros a b c d e f eq1 eq2.
  transitivity [c;d].
  apply eq1. apply eq2.   Qed.
```

归纳类型定义的特点

- Injection: 同一个构造子传不同参数时构造的值不同,
  - 即构造子为单射
  - 即S n = S m -> n = m

```
Inductive nat : Type :=
  | O
  | S (n : nat).
```

- Disjointness: 不同的构造子构造的值均不同,
  - 即S n = 0不可能成立
- 利用这些特点可以完成一些证明，Rocq也提供了相应的策略支持

证明单射

声明一个新的引理，然后证明这个引理。

- 单射可以通过定义函数来返回构造子实参证明

```
Theorem S_injective : forall (n m : nat),
  S n = S m -> n = m.
Proof. intros n m H1.
  assert (H2: n = pred (S n)). { reflexivity. }
  (* n, m : nat
  *   H1 : S n = S m
  *   H2 : n = Nat.pred (S n)
  *   =======================
  *   n = m
  *)
  rewrite H2.
  (*  Nat.pred (S n) = m *)
  rewrite H1.
  (*  Nat.pred (S m) = m *)
  reflexivity. Qed.
```

```
Definition pred (n : nat) : nat :=
  match n with
  | O => O
  | S n' => n'
  end.
```

injection策略

- injection策略根据构造子的单射性推导参数的等价性

```
Theorem S_injective' : forall (n m : nat),
  S n = S m ->
  n = m.
Proof. intros n m H.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   H : S n = S m
 *   =============
 *   n = m
 *)
```

injection策略

- injection策略根据构造子的单射性推导参数的等价性

```
  injection H as Hnm.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   Hnm : n = m
 *   ===========
 *   n = m
 *)
  apply Hnm.
Qed.
```

injection策略

- as部分可以省略，省略后推出的等式加入目标

```
  injection H.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   H: S n = S m
 *   ===========
 *   n = m -> n = m
 *)
  intros Hnm. apply Hnm.
Qed.
```

injection策略

- 也可以递归推出多个等式

```
Theorem injection_ex1 : forall (n m o : nat),
  [n;m] = [o;o] ->
  n = m.
Proof.
  intros n m o H.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m, o : nat
 *   H : [n; m] = [o; o]
 *   ===================
 *   n = m
 *)
```

注意[n;m]等价于
cons n (cons m nil)

injection策略

- 也可以递归推出多个等式

```
  injection H as H1 H2.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m, o : nat
 *   H1 : n = o
 *   H2 : m = o
 *   =============
 *   n = m
 *)
  rewrite H1. rewrite H2. reflexivity.
Qed.
```

injection的逆：f_equal

对任意函数都成立

```
Theorem f_equal : forall (A B : Type) (f: A -> B) (x y: A),
  x = y -> f x = f y.
Proof. intros A B f x y eq. rewrite eq.  reflexivity.  Qed.

Theorem eq_implies_succ_equal : forall (n m : nat),
  n = m -> S n = S m.
Proof. intros n m H. apply f_equal. apply H. Qed.

Theorem eq_implies_succ_equal' : forall (n m : nat),
  n = m -> S n = S m.
Proof. intros n m H. f_equal. apply H. Qed.
```

注意injection应用到假设上，
f_equal应用到目标上

discriminate策略

- 如果假设包含不同构造子构造的值形成了等式，则直接判断结论成立
  - 爆炸原理：False推导出任意结论

```
Theorem discriminate_ex1 : forall (n m : nat),
  false = true ->
  n = m.
Proof. intros n m contra.
(* 1 subgoal
 *
 *   n, m : nat
 *   contra : false = true
 *   ======================
 *   n = m
 *)
 discriminate contra.(** No more subgoals. *)
 Qed.
```

参数可省略，discriminate会自动寻找矛盾的假设

discriminate策略

- discriminate会自动应用simpl，并递归到深层构造子

```
Theorem discriminate_ex2 : forall (n : nat),
  pred (S (S (S n))) = S O ->
  2 + 2 = 5.
Proof.
  intros n contra.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n : nat
 *   contra : Nat.pred (S (S (S n))) = 1
 *   ================
 *   2 + 2 = 5
 *)
  discriminate. Qed.
```

将策略应用到假设

- 在适用的策略后面加上”in H”能将策略应用到假设H

```
Theorem S_inj : forall (n m : nat) (b : bool),
  ((S n) =? (S m)) = b  ->
  (n =? m) = b.
Proof. intros n m b H.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   b : bool
 *   H : (S n =? S m) = b
 *   ====================
 *   (n =? m) = b
 *)
```

将策略应用到假设

- 在适用的策略后面加上”in H”能将策略应用到假设H

```
simpl in H.(** [Rocq Proof View]
* 1 subgoal
*
*    n, m : nat
*    b : bool
*    H : (n =? m) = b
*    ================
*    (n =? m) = b
*)
apply H.(** No more subgoals. *)
Qed.
```

将策略应用到假设

- 等价变换策略应用到目标和假设上效果相同

```
Theorem silly4 : forall (n m p q : nat),
  (n = m -> p = q) ->
  m = n ->
  q = p.
Proof. intros n m p q EQ H.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m, p, q : nat
 *   EQ : n = m -> p = q
 *   H : m = n
 *   ===================
 *   q = p
 *)
```

将策略应用到假设

- 等价变换策略应用到目标和假设上效果相同

```
 symmetry in H.(** [Rocq Proof View]
* 1 subgoal
*
*   n, m, p, q : nat
*   EQ : n = m -> p = q
*   H : n = m
*   ===================
*   q = p
*)
```

将策略应用到假设

- 不等价变换应用时方向相反
  - 给定H:P->Q，apply H将目标从Q替换为P，apply H in H1将H1从P替换到Q

```
apply EQ in H.(** [Rocq Proof View]
* 1 subgoal
*
*   n, m, p, q : nat
*   EQ : n = m -> p = q
*   H : p = q
*   ===================
*   q = p
*)
symmetry in H. apply H. Qed.
```

specialize策略

- 用于将全称量词下的变量替换成具体值

```
Theorem specialize_example: forall n,
     (forall m, m*n = 0)-> n = 0.
Proof.
  intros n H.
  (* n: nat
   * H: forall m : nat, m * n = 0
   * ====================================
   * n = 0
   *)
  specialize H with (m := 1).
  (* H: 1 * n = 0
     multi_1_l : forall n:nat, 1 * n = n.*)
  rewrite multi_1_l in H. apply H. Qed.
```

specialize策略

- 替换的也可以是系统定理

```
Theorem plus_rearrange : forall n m p q : nat,
  (n + m) + (p + q) = (m + n) + (p + q).
Proof.
  intros n m p q.
  (*
   * assert (H: n + m = m + n).
   * { rewrite add_comm. reflexivity. }
   *)
  specialize add_comm with (n:=n) (m:=m) as H.
  rewrite H. reflexivity.  Qed.
```

将替换后的定理保存为H。如不加，则将目标改写为H->Goal的形式。

一个失败的归纳证明过程

```
Theorem double_injective_FAILED : forall n m,
  double n = double m ->
  n = m.
Proof.
  intros n m. induction n as [| n' IHn'].
  - (* n = O *) simpl. intros eq. destruct m as [| m'] eqn:E.
    + (* m = O *) reflexivity.
    + (* m = S m' *) discriminate eq.
  - (* n = S n' *) intros eq. destruct m as [| m'] eqn:E.
    + (* m = O *) discriminate eq.
    + (* m = S m' *)
```

一个失败的归纳证明过程

```
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n', m, m' : nat
 *   E : m = S m'
 *   IHn' : double n' = double (S m') -> n' = S m'
 *   eq : double (S n') = double (S m')
 *   ============================================
 *   S n' = S m'
 *)
Abort.
```

前提不为真，自然可以有任意结论，该归纳假设完全无用

为什么失败

- 自然数上归纳证明P的过程
  - 证明$P(0)$
  - 证明$\forall n, P(n) \rightarrow P(S\ n)$
- 这个例子中，$P(n) \equiv \forall m, P'(n, m)$
  - 其中$P'(n, m) \equiv double\ n = double\ m \rightarrow n = m$
- 即，我们需要证明
  - $\forall m, P'(0, m)$
  - $\forall n, \left(\forall m, P'(n, m)\right) \rightarrow \left(\forall m, P'(S\ n, m)\right)$
- 但实际我们证明的是
  - $\forall m, P'(0, m)$
  - $\forall n, \forall m, \left(P'(n, m) \rightarrow P'(S\ n, m)\right) \equiv$
    $\forall n, \forall m, \Big((double\ n = double\ m \rightarrow n = m)$
    $\rightarrow (double\ S\ n = double\ m \rightarrow S\ n = m)\Big)$
- Coq规则：已经在假设区的变量不作为自由变量放入归纳假设

解决方案1

- 不主动intro额外的变量

intro n可以省略，induction n自动引入n和n之前的变量

```
Theorem double_injective : forall n m,
  double n = double m -> n = m.
Proof. intro n. induction n as [| n' IHn'].
  - (* n = O *) simpl. intros m eq. destruct m as [| m'] eqn:E.
    + (* m = O *) reflexivity.
    + (* m = S m' *) discriminate eq.
  - (* n = S n’ *)
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n' : nat
 *   IHn' : forall m : nat, double n' = double m -> n' = m
 *   ========================================
 *   forall m : nat, double (S n') = double m -> S n' = m
 *)
```

解决方案1

自动intros n m.

- 该方法在归纳变量不在第一位时会出问题

```
Theorem double_injective_take2_FAILED2 : forall n m,
  double n = double m -> n = m.
Proof. induction m.
  - (* m = O *) simpl. intros. destruct n as [| n'] eqn:E.
    + (* n = O *) reflexivity.
    + (* n = S n' *) discriminate H.
  - (* n = S n’ *)
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m: nat
 *   IHm: double n = double m -> n = m
 *   =====================================================
 *   double n = double (S m) -> n = S m
 *)
```

解决方案2

- 采用generalize dependent策略

```
Theorem double_injective_take2 : forall n m,
  double n = double m -> n = m.
Proof.
  intros n m.
(*   n, m : nat
 *   ============================
 *   double n = double m -> n = m
 *)
  generalize dependent n.
(*   m : nat
 *   ============================================
 *   forall n : nat, double n = double m -> n = m
 *)
```

解决方案2

- 采用generalize dependent策略

```
  induction m as [| m' IHm'].
  - (* m = O *) simpl. intros n eq. destruct n as [| n'] eqn:E.
    + (* n = O *) reflexivity.
    + (* n = S n' *) discriminate eq.
  - (* m = S m' *)
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   m' : nat
 *   IHm' : forall n : nat, double n = double m' -> n = m'
 *   =====================================================
 *   forall n : nat, double n = double (S m') -> n = S m'
 *)
```

Unfold策略——动机

```
Definition square n := n * n.

Lemma square_mult : forall n m,
  square (n * m) = square n * square m.
Proof.
  intros n m.
(*   n, m : nat
 *   ============================
 *   square (n * m) = square n * square m
 *)
  simpl.
(*   n, m : nat
 *   ============================
 *   square (n * m) = square n * square m
 *)
```

为什么square没有被展开？Rocq只在能展开match或者展开fixpoint的时候进行约简，否则不变。

Unfold策略

```
  unfold square.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n, m : nat
 *   =================================
 *   n * m * (n * m) = n * n * (m * m)
 *)
  rewrite mult_assoc.
  assert (H : n * m * n = n * n * m).
    { rewrite mul_comm. apply mult_assoc. }
  rewrite H. rewrite mult_assoc. reflexivity.
Qed.
```

将目标中的square展开。也可以加上in H用于假设H。

更多simpl的例子

```
Definition foo (x: nat) := 5.

Fact silly_fact_1 : forall m, foo m + 1 = foo (m + 1) + 1.
Proof.
  intros m.
(*   m : nat
 *   ===========================
 *   foo m + 1 = foo (m + 1) + 1
 *)
  simpl.
(*   m : nat
 *   =======
 *   6 = 6
 *)
```

结果是什么？

更多simpl的例子

```
Definition foo (x: nat) := 5.

Fact silly_fact_1' : forall m, foo m = foo (m + 1).
Proof.
  intros m.
(*   m : nat
 *   ===========================
 *   foo m = foo (m + 1)
 *)
  simpl.
(*   m : nat
 *   =======
 *   foo m = foo (m + 1)
 *)
  reflexivity. Qed.
```

结果是什么？

更多simpl的例子

```
Definition bar x :=
  match x with
  | O => 5
  | S _ => 5
  end.

Fact silly_fact_2_FAILED : forall m, bar m + 1 = bar (m + 1) + 1.
Proof.
  intros m.
(*   m : nat
 *   ===========================
 *   bar m + 1 = bar (m + 1) + 1
 *)
  simpl.
(*   m : nat
 *   ===========================
 *   bar m + 1 = bar (m + 1) + 1
 *)
```

结果是什么？

采用destruct分解表达式

```
Definition sillyfun (n : nat) : bool :=
  if n =? 3 then false
  else if n =? 5 then false
  else false.

Theorem sillyfun_false : forall (n : nat),
  sillyfun n = false.
Proof. intros n. unfold sillyfun.
(** [Rocq Proof View]
 * 1 subgoal
 *
 *   n : nat
 *   ============================================================
 *   (if n =? 3 then false else if n =? 5 then false else false)
 *   = false
 *)
```

如何证明?

采用destruct分解表达式

- 虽然可以用destruct n证明，但过于麻烦

```
Theorem sillyfun_false : forall (n : nat),
  sillyfun n = false.
Proof. intros n. unfold sillyfun.
  destruct n. reflexivity.
  destruct n. reflexivity.
  destruct n. reflexivity.
  destruct n. reflexivity.
  destruct n. reflexivity.
  destruct n. reflexivity.
  reflexivity.
Qed.
```

采用destruct分解表达式

```
   destruct (n =? 3) eqn:E1.
 (** [Rocq Proof View]
  * 2 subgoals
  *
  *   n : nat
  *   E1 : (n =? 3) = true
  *   ========================================
  *   false = false
  *
  * subgoal 2 is:
  *  (if n =? 5 then false else false) = false
  *)
     - (* n =? 3 = true *) reflexivity.
     - (* n =? 3 = false *) destruct (n =? 5) eqn:E2.
       + (* n =? 5 = true *) reflexivity.
       + (* n =? 5 = false *) reflexivity.  Qed.
```

分解表达式时eqn:H往往关键

```
Definition sillyfun1 (n : nat) : bool :=
  if n =? 3 then true
  else if n =? 5 then true
  else false.

Theorem sillyfun1_odd_FAILED : forall (n : nat),
  sillyfun1 n = true -> odd n = true.
Proof.
  intros n eq. unfold sillyfun1 in eq.
  destruct (n =? 3).
(*   n : nat
 *   eq : true = true
 *   ================
 *   odd n = true
 *
 * subgoal 2 is:
 *  odd n = true
 *)
Abort.
```

分解表达式时eqn:H往往关键

```
Theorem sillyfun1_odd : forall (n : nat),
  sillyfun1 n = true ->
  odd n = true.
Proof.
  intros n eq. unfold sillyfun1 in eq.
  destruct (n =? 3) eqn:Heqe3.
    - (* e3 = true *) apply eqb_true in Heqe3.
      rewrite -> Heqe3. reflexivity.
    - (* e3 = false *)
      destruct (n =? 5) eqn:Heqe5.
        + (* e5 = true *)
          apply eqb_true in Heqe5.
          rewrite -> Heqe5. reflexivity.
        + (* e5 = false *) discriminate eq.  Qed.
```

策略总结

- `intros`: move hypotheses/variables from goal to context
- `reflexivity`: finish the proof (when the goal looks like `e = e`)
- `apply`: prove goal using a hypothesis, lemma, or constructor
- `apply... in H`: apply a hypothesis, lemma, or constructor to a hypothesis in the context (forward reasoning)
- `apply... with...`: explicitly specify values for variables that cannot be determined by pattern matching
- `simpl`: simplify computations in the goal
- `simpl in H`: ... or a hypothesis

策略总结

- `rewrite`: use an equality hypothesis (or lemma) to rewrite the goal
- `rewrite ... in H`: ... or a hypothesis
- `symmetry`: changes a goal of the form `t=u` into `u=t`
- `symmetry in H`: changes a hypothesis of the form `t=u` into `u=t`
- `transitivity y`: prove a goal `x=z` by proving two new subgoals, `x=y` and `y=z`
- `unfold`: replace a defined constant by its right-hand side in the goal
- `unfold... in H`: ... or a hypothesis

策略总结

- `destruct... as...`: case analysis on values of inductively defined types
- `destruct... eqn:...`: specify the name of an equation to be added to the context, recording the result of the case analysis
- `induction... as...`: induction on values of inductively defined types
- `injection... as...`: reason by injectivity on equalities between values of inductively defined types

策略总结

- `discriminate`: reason by disjointness of constructors on equalities between values of inductively defined types
- `assert (H: e)` (or `assert (e) as H`): introduce a "local lemma" `e` and call it `H`
- `generalize dependent x`: move the variable `x` (and anything else that depends on it) from the context back to an explicit hypothesis in the goal formula
- `f_equal`: change a goal of the form `f x = f y` into `x = y`

作业

- 完成Tactics.v中standard非optional且不属于Additional Exercises的9道习题
  - 请使用最新英文版教材