CS156: The Calculus of Computation

Zohar Manna
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Chapter 4: Induction

Induction

- Stepwise induction (for T_{PA}, T_{cons})
- Complete induction (for T_{PA}, T_{cons})
  Theoretically equivalent in power to stepwise induction, but sometimes produces more concise proof
- Well-founded induction
  Generalized complete induction
- Structural induction
  Over logical formulae

Stepwise Induction (Peano Arithmetic T_{PA})

Axiom schema (induction)

$$\begin{array}{ll} F[0] \wedge & \ldots \text{ base case} \\ (\forall n.\ F[n] \ \rightarrow \ F[n+1]) & \ldots \text{ inductive step} \\ \rightarrow \ \forall x.\ F[x] & \ldots \text{ conclusion} \end{array}$$

for Σ_{PA}-formulae $F[x]$ with one free variable x.

To prove $\forall x.\ F[x]$, the conclusion, i.e.,
$F[x]$ is T_{PA}-valid for all $x \in \mathbb{N}$,
it suffices to show

- base case: prove $F[0]$ is T_{PA}-valid.
- inductive step: For arbitrary $n \in \mathbb{N}$,
  assume inductive hypothesis, i.e.,
  $F[n]$ is T_{PA}-valid,
  then prove
  $F[n+1]$ is T_{PA}-valid.

Example

Prove:

$$F[n] : 1 + 2 + \cdots + n = \frac{n(n+1)}{2}$$

for all $n \in \mathbb{N}$.

- *Base case*: $F[0] : 0 = \frac{0 \cdot 1}{2}$
- *Inductive step*: Assume $F[n] : 1 + 2 + \cdots + n = \frac{n(n+1)}{2}$, (IH)
  show

$$\begin{array}{lcll} F[n+1] & : & 1 + 2 + \cdots + n + (n+1) & \\ & = & \dfrac{n(n+1)}{2} + (n+1) & \text{by } (IH) \\ & = & \dfrac{n(n+1) + 2(n+1)}{2} & \\ & = & \dfrac{(n+1)(n+2)}{2} & \end{array}$$

Therefore,

$$\forall n \in \mathbb{N}.\ 1 + 2 + \ldots + n = \frac{n(n+1)}{2}$$

Example:

Theory T_{PA}^{+} obtained from T_{PA} by adding the axioms:

- $\forall x.\ x^0 = 1$ (E0)
- $\forall x, y.\ x^{y+1} = x^y \cdot x$ (E1)
- $\forall x, z.\ exp_3(x, 0, z) = z$ (P0)
- $\forall x, y, z.\ exp_3(x, y+1, z) = exp_3(x, y, x \cdot z)$ (P1)

($exp_3(x, y, z)$ stands for $x^y.z$)

Prove that

$$\boxed{\forall x, y.\ exp_3(x, y, 1) = x^y}$$

is T_{PA}^{+}-valid.

First attempt:

$$\forall y\ [\underbrace{\forall x.\ exp_3(x, y, 1) = x^y}_{F[y]}]$$

We chose induction on y. Why?

Base case:

$F[0]:\ \forall x.\ exp_3(x, 0, 1) = x^0$

For arbitrary $x \in \mathbb{N}$, $exp_3(x, 0, 1) = 1$ (P0) and $x^0 = 1$ (E0).

Inductive step: Failure.

For arbitrary $n \in \mathbb{N}$, we cannot deduce

$F[n+1] : \forall x.\ exp_3(x, n+1, 1) = x^{n+1}$

from the inductive hypothesis

$F[n] : \forall x.\ exp_3(x, n, 1) = x^n$

Second attempt: Strengthening

Strengthened property

$$\boxed{\forall x, y, z.\ exp_3(x, y, z) = x^y \cdot z}$$

Implies the desired property (choose $z = 1$)

$\forall x, y.\ exp_3(x, y, 1) = x^y$

Proof of strengthened property:

Again, induction on y

$$\forall y\ [\underbrace{\forall x, z.\ exp_3(x, y, z) = x^y \cdot z}_{F[y]}]$$

Base case:

$F[0]:\ \forall x, z.\ exp_3(x, 0, z) = x^0 \cdot z$

For arbitrary $x, z \in \mathbb{N}$, $exp_3(x, 0, z) = z$ (P0) and $x^0 = 1$ (E0).

Inductive step: For arbitrary $n \in \mathbb{N}$

Assume inductive hypothesis

$F[n] : \forall x, z.\ exp_3(x, n, z) = x^n \cdot z$ (IH)

prove

$F[n+1] : \forall x', z'.\ exp_3(x', n+1, z') = x'^{n+1} \cdot z'$

$\uparrow$note

Consider arbitrary $x', z' \in \mathbb{N}$:

$$\begin{aligned} exp_3(x', n+1, z') &= exp_3(x', n, x' \cdot z') && \text{(P1)} \\ &= x'^n \cdot (x' \cdot z') && \text{IH } F[n]; x \mapsto x', z \mapsto x' \cdot z' \\ &= x'^{n+1} \cdot z' && \text{(E1)} \end{aligned}$$

Stepwise Induction (Lists T_{cons})

Axiom schema (induction)

$$\begin{array}{ll} (\forall \text{ atom } u.\ F[u]) \wedge & \ldots \text{ base case} \\ (\forall u, v.\ F[v] \ \rightarrow\ F[\text{cons}(u, v)]) & \ldots \text{ inductive step} \\ \ \rightarrow\ \forall x.\ F[x] & \ldots \text{ conclusion} \end{array}$$

for Σ_{cons}-formulae $F[x]$ with one free variable x.

Note: $\forall$ atom u. $F[u]$ stands for $\forall u.\ (\text{atom}(u)\ \rightarrow\ F[u])$.

To prove $\forall x.\ F[x]$, i.e.,

$F[x]$ is T_{cons}-valid for all lists x,

it suffices to show

- base case: prove $F[u]$ is T_{cons}-valid for arbitrary atom u.
- inductive step: For arbitrary lists u, v,
  assume inductive hypothesis, i.e.,
  $F[v]$ is T_{cons}-valid,
  then prove
  $F[\text{cons}(u, v)]$ is T_{cons}-valid.

Example: Theory T^{+}_{cons} I

T_{cons} with axioms

Concatenating two lists

- $\forall$ atom u. $\forall v.concat(u, v) = cons(u, v)$ (C0)
- $\forall u, v, x.\ concat(\text{cons}(u, v), x) = \text{cons}(u, concat(v, x))$ (C1)

Example: Theory T^{+}_{cons} II

Example: for atoms a, b, c, d,

$$\begin{array}{lll} & concat(\text{cons}(a, \text{cons}(b, c)), d) & \\ = & \text{cons}(a, concat(\text{cons}(b, c), d)) & (C1) \\ = & \text{cons}(a, \text{cons}(b, concat(c, d))) & (C1) \\ = & \text{cons}(a, \text{cons}(b, \text{cons}(c, d))) & (C0) \end{array}$$

$$\begin{array}{lll} & concat(\text{cons}(\text{cons}(a, b), c), d) & \\ = & \text{cons}(\text{cons}(a, b), concat(c, d)) & (C1) \\ = & \text{cons}(\text{cons}(a, b), \text{cons}(c, d)) & (C0) \end{array}$$

Example: Theory T^{+}_{cons} III

Reversing a list

- $\forall$ atom u. $rvs(u) = u$ (R0)
- $\forall x, y.\ rvs(concat(x, y)) = concat(rvs(y), rvs(x))$ (R1)

Example: for atoms a, b, c,

$$\begin{array}{lll} & rvs(\text{cons}(a, \text{cons}(b, c)) & \\ = & rvs(concat(a, concat(b, c))) & (C0) \\ = & concat(rvs(concat(b, c)), rvs(a)) & (R1) \\ = & concat(concat(rvs(c), rvs(b)), rvs(a)) & (R1) \\ = & concat(concat(c, b), a) & (R0) \\ = & concat(\text{cons}(c, b), a) & (C0) \\ = & \text{cons}(c, concat(b, a)) & (C1) \\ = & \text{cons}(c, \text{cons}(b, a)) & (C0) \end{array}$$

Example: Theory T^+_{cons} IV

Deciding if a list is flat;

i.e., $\mathit{flat}(x)$ is true iff every element of list x is an atom.

- $\forall$ atom u. $\mathit{flat}(u)$ (F0)
- $\forall u, v.\ \mathit{flat}(\text{cons}(u, v)) \leftrightarrow \text{atom}(u) \wedge \mathit{flat}(v)$ (F1)

Example: for atoms a, b, c,

$$\begin{aligned} \mathit{flat}(\text{cons}(a, \text{cons}(b, c))) &= \text{true} \\ \mathit{flat}(\text{cons}(\text{cons}(a, b), c)) &= \text{false} \end{aligned}$$

Prove

$$\boxed{\forall x.\ \underbrace{\mathit{flat}(x) \ \rightarrow\ \mathit{rvs}(\mathit{rvs}(x)) = x}_{F[x]}}$$

is T^+_{cons}-valid.

Base case: For arbitrary atom u,

$$F[u] : \mathit{flat}(u) \ \rightarrow\ \mathit{rvs}(\mathit{rvs}(u)) = u$$

by $F0$ and R0.

Inductive step: For arbitrary lists u, v, assume the inductive hypothesis

$$F[v] :\ \mathit{flat}(v) \ \rightarrow\ \mathit{rvs}(\mathit{rvs}(v)) = v \qquad \text{(IH)}$$

and prove

$$\begin{aligned} F[\text{cons}(u, v)] \ &:\ \mathit{flat}(\text{cons}(u, v)) \ \rightarrow \\ &\qquad \mathit{rvs}(\mathit{rvs}(\text{cons}(u, v))) = \text{cons}(u, v) \qquad (*) \end{aligned}$$

Case $\neg\text{atom}(u)$

$$\mathit{flat}(\text{cons}(u, v)) \ \Leftrightarrow\ \text{atom}(u) \wedge \mathit{flat}(v) \ \Leftrightarrow\ \perp$$

by (F1). $(*)$ holds since its antecedent is $\perp$.

Case $\text{atom}(u)$

$$\mathit{flat}(\text{cons}(u, v)) \ \Leftrightarrow\ \text{atom}(u) \wedge \mathit{flat}(v) \ \Leftrightarrow\ \mathit{flat}(v)$$

by (F1). Now, show

$$\mathit{rvs}(\mathit{rvs}(\text{cons}(u, v))) = \cdots = \text{cons}(u, v).$$

Missing steps:

$$\begin{aligned} & \mathit{rvs}(\mathit{rvs}(\text{cons}(u, v))) \\ =\ & \mathit{rvs}(\mathit{rvs}(\mathit{concat}(u, v))) && \text{(C0)} \\ =\ & \mathit{rvs}(\mathit{concat}(\mathit{rvs}(v), \mathit{rvs}(u))) && \text{(R1)} \\ =\ & \mathit{concat}(\mathit{rvs}(\mathit{rvs}(u)), \mathit{rvs}(\mathit{rvs}(v))) && \text{(R1)} \\ =\ & \mathit{concat}(u, \mathit{rvs}(\mathit{rvs}(v))) && \text{(R0)} \\ =\ & \mathit{concat}(u, v) && \text{(IH), since } \mathit{flat}(v) \\ =\ & \text{cons}(u, v) && \text{(C0)} \end{aligned}$$

Complete Induction (Peano Arithmetic T_{PA})

Axiom schema (complete induction)

$$(\forall n.\ (\underbrace{\forall n'.\ n' < n\ \rightarrow\ F[n']}_{IH})\ \rightarrow\ F[n]) \qquad \ldots \text{ inductive step}$$

$$\rightarrow\ \forall x.\ F[x] \qquad \ldots \text{ conclusion}$$

for Σ_{PA}-formulae $F[x]$ with one free variable x.

To prove $\forall x.\ F[x]$, the conclusion i.e.,

$F[x]$ is T_{PA}-valid for all $x \in \mathbb{N}$,

it suffices to show

- inductive step: For arbitrary $n \in \mathbb{N}$,
  assume inductive hypothesis, i.e.,
  $F[n']$ is T_{PA}-valid for every $n' \in \mathbb{N}$ such that $n' < n$,
  then prove
  $F[n]$ is T_{PA}-valid.

Is base case missing?

No. Base case is implicit in the structure of complete induction.

Note:

- Complete induction is theoretically equivalent in power to stepwise induction.
- Complete induction sometimes yields more concise proofs.

Example: Integer division $\quad quot(5,3) = 1$ and $rem(5,3) = 2$

Theory T^*_{PA} obtained from T_{PA} by adding the axioms:

- $\forall x, y.\ x < y\ \rightarrow\ quot(x,y) = 0$ (Q0)
- $\forall x, y.\ y > 0\ \rightarrow\ quot(x+y, y) = quot(x,y) + 1$ (Q1)
- $\forall x, y.\ x < y\ \rightarrow\ rem(x,y) = x$ (R0)
- $\forall x, y.\ y > 0\ \rightarrow\ rem(x+y, y) = rem(x,y)$ (R1)

Prove

(1) $\forall x, y.\ y > 0\ \rightarrow\ rem(x,y) < y$

(2) $\forall x, y.\ y > 0\ \rightarrow\ x = y \cdot quot(x,y) + rem(x,y)$

Best proved by complete induction.

Proof of (1)

$$\forall x.\ \underbrace{\forall y.\ y > 0\ \rightarrow\ rem(x,y) < y}_{F[x]}$$

Consider an arbitrary natural number x.

Assume the inductive hypothesis

$$\forall x'.\ x' < x\ \rightarrow\ \underbrace{\forall y'.\ y' > 0\ \rightarrow\ rem(x',y') < y'}_{F[x']} \qquad \text{(IH)}$$

Prove $\quad F[x] : \forall y.\ y > 0\ \rightarrow\ rem(x,y) < y.$

Let y be an arbitrary positive integer

Case $x < y$:

$$\begin{array}{rcll} rem(x,y) & = & x & \text{by (R0)} \\ & < & y & \text{case} \end{array}$$

Case $\neg(x < y)$:

Then there is natural number n, $n < x$ s.t. $x = n + y$

$$\begin{array}{rcll} rem(x,y) & = & rem(n+y, y) & x = n + y \\ & = & rem(n,y) & \text{(R1)} \\ & < & y & \text{IH } (x' \mapsto n, y' \mapsto y) \\ & & & \text{since } n < x \text{ and } y > 0 \end{array}$$

Well-founded Induction I

A binary predicate $\prec$ over a set S is a well-founded relation iff there does not exist an infinite decreasing sequence

$s_1 \succ s_2 \succ s_3 \succ \cdots$ where $s_i \in S$

Note: where $s \prec t$ iff $t \succ s$

Examples:

- $<$ is well-founded over the natural numbers.
  Any sequence of natural numbers decreasing according to $<$ is finite:
  $$1023 > 39 > 30 > 29 > 8 > 3 > 0.$$
- $<$ is not well-founded over the rationals in $[0, 1]$.
  $$1 > \frac{1}{2} > \frac{1}{3} > \frac{1}{4} > \cdots$$
  is an infinite decreasing sequence.

Well-founded Induction II

- $<$ is not well-founded over the integers:
  $$7200 > \ldots > 217 > \ldots > 0 > \ldots > -17 > \ldots$$
- The strict sublist relation $\prec_c$ is well-founded over the set of all lists.
- The relation
  $$F \prec G \text{ iff } F \text{ is a strict subformula of } G$$
  is well-founded over the set of formulae.

Well-founded Induction Principle

For theory T and well-founded relation $\prec$,
the axiom schema (well-founded induction)

$$(\forall n.\ (\forall n'.\ n' \prec n \ \rightarrow\ F[n'])\ \rightarrow\ F[n])\ \rightarrow\ \forall x.\ F[x]$$

for Σ-formulae $F[x]$ with one free variable x.

To prove $\forall x.\ F[x]$, i.e.,
$F[x]$ is T-valid for every x,
it suffices to show

- inductive step: For arbitrary n,
  assume inductive hypothesis, i.e.,
  $F[n']$ is T-valid for every n', such that $n' \prec n$
  then prove
  $F[n]$ is T-valid.

Complete induction in T_{PA} is a specific instance of well-founded induction, where the well-founded relation $\prec$ is $<$.

Lexicographic Relation

Given pairs $(S_i, \prec_i)$ of sets S_i and well-founded relations $\prec_i$

$$(S_1, \prec_1), \ldots, (S_m, \prec_m)$$

Construct

$$S = S_1 \times \ldots \times S_m;$$

i.e., the set of m-tuples $(s_1, \ldots, s_m)$ where each $s_i \in S_i$.

Define lexicographic relation $\prec$ over S as

$$\underbrace{(s_1, \ldots, s_m)}_{s} \prec \underbrace{(t_1, \ldots, t_m)}_{t} \ \Leftrightarrow\ \bigvee_{i=1}^{m} \left(s_i \prec_i t_i \wedge \bigwedge_{j=1}^{i-1} s_j = t_j \right)$$

for $s_i, t_i \in S_i$.

- If $(S_1, \prec_1), \ldots, (S_m, \prec_m)$ are well-founded, so is $(S, \prec)$.

Example: $S = \{A, \cdots, Z\}$, $m = 3$, $CAT \prec DOG$, $DOG \prec DRY$, $DOG \prec DOT$.

Example: For the set $\mathbb{N}^3$ of triples of natural numbers with the lexicographic relation $\prec$,

$$(5, 2, 17) \prec (5, 4, 3)$$

Lexicographic well-founded induction principle

For theory T and well-founded lexicographic relation $\prec$,

$$(\forall \bar{n}.\ (\forall \bar{n}'.\ \bar{n}' \prec \bar{n} \ \rightarrow\ F[\bar{n}']) \ \rightarrow\ F[\bar{n}]) \ \rightarrow\ \forall \bar{x}.\ F[\bar{x}]$$

for Σ_T-formula $F[\bar{x}]$ with free variables $\bar{x}$, is T-valid.

Same as regular well-founded induction, just

$$n \ \Rightarrow\ \text{tuple } \bar{n} = (n_1, \ldots, n_m) \quad x \ \Rightarrow\ \text{tuple } \bar{x} = (x_1, \ldots, x_m)$$
$$n' \ \Rightarrow\ \text{tuple } \bar{n}' = (n'_1, \ldots, n'_m)$$

Example: Puzzle

Bag of red, yellow, and blue chips

If one chip remains in the bag – remove it (empty bag – the process terminates)

Otherwise, remove two chips at random:

1. If one of the two is red –
   don't put any chips in the bag
2. If both are yellow –
   put one yellow and five blue chips
3. If one of the two is blue and the other not red –
   put ten red chips

Does this process terminate?

Proof: Consider

- Set $S : \mathbb{N}^3$ of triples of natural numbers and

- Well-founded lexicographic relation $<_3$ for such triples, e.g.

$$(11, 13, 3) \not<_3 (11, 9, 104) \qquad (11, 9, 104) <_3 (11, 13, 3)$$

Let y, b, r be the yellow, blue, and red chips in the bag before a move.

Let y', b', r' be the yellow, blue, and red chips in the bag after a move.

Show

$$(y', b', r') <_3 (y, b, r)$$

for each possible case. Since $<_3$ well-founded relation $\Rightarrow$ only finite decreasing sequences $\Rightarrow$ process must terminate

1. If one of the two removed chips is red –
   do not put any chips in the bag

$$\left.\begin{matrix} (y-1, b, r-1) \\ (y, b-1, r-1) \\ (y, b, r-2) \end{matrix}\right\} <_3 (y, b, r)$$

2. If both are yellow –
   put one yellow and five blue

$$(y-1, b+5, r) <_3 (y, b, r)$$

3. If one is blue and the other not red –
   put ten red

$$\left.\begin{matrix} (y-1, b-1, r+10) \\ (y, b-2, r+10) \end{matrix}\right\} <_3 (y, b, r)$$

Example: Ackermann function

Theory $T_{\mathbb{N}}^{ack}$ is the theory of Presburger arithmetic $T_{\mathbb{N}}$ (for natural numbers) augmented with

Ackermann axioms:

- $\forall y.\ ack(0, y) = y + 1$ (L0)
- $\forall x.\ ack(x + 1, 0) = ack(x, 1)$ (R0)
- $\forall x, y.\ ack(x + 1, y + 1) = ack(x, ack(x + 1, y))$ (S)

Ackermann function grows quickly:

$ack(0, 0) = 1$
$ack(1, 1) = 3$
$ack(2, 2) = 7$
$ack(3, 3) = 61$

$$ack(4, 4) = 2^{2^{2^{2^{16}}}} - 3$$

Proof of termination

Let $<_2$ be the lexicographic extension of $<$ to pairs of natural numbers.

(L0) $\forall y.\ ack(0, y) = y + 1$
does not involve recursive call

(R0) $\forall x.\ ack(x + 1, 0) = ack(x, 1)$
$(x + 1, 0) >_2 (x, 1)$

(S) $\forall x, y.\ ack(x + 1, y + 1) = ack(x, ack(x + 1, y))$
$(x + 1, y + 1) >_2 (x + 1, y)$
$(x + 1, y + 1) >_2 (x, ack(x + 1, y))$

No infinite recursive calls $\Rightarrow$ the recursive computation of $ack(x, y)$ terminates for all pairs of natural numbers.

Proof of property

Use well-founded induction over $<_2$ to prove

$$\forall x, y.\ ack(x, y) > y$$

is $T_{\mathbb{N}}^{ack}$ valid.

Consider arbitrary natural numbers x, y.
Assume the inductive hypothesis

$$\forall x', y'.\ (x', y') <_2 (x, y) \rightarrow \underbrace{ack(x', y') > y'}_{F[x', y']} \quad \text{(IH)}$$

Show

$$F[x, y] : ack(x, y) > y.$$

Case $x = 0$:

$$ack(0, y) = y + 1 > y \qquad \text{by (L0)}$$

Case $x > 0 \wedge y = 0$:

$$ack(x, 0) = ack(x - 1, 1) \qquad \text{by (R0)}$$

Since

$$(\underbrace{x - 1}_{x'}, \underbrace{1}_{y'}) <_2 (x, y)$$

Then

$$ack(x - 1, 1) > 1 \qquad \text{by (IH) } (x' \mapsto x - 1, y' \mapsto 1)$$

Thus

$$ack(x, 0) = ack(x - 1, 1) > 1 > 0$$

Case $x > 0 \land y > 0$:

$$ack(x, y) = ack(x-1, ack(x, y-1)) \qquad \text{by (S)} \qquad (1)$$

Since

$$(\underbrace{x-1}_{x'}, \underbrace{ack(x, y-1)}_{y'}) <_2 (x, y)$$

Then

$$ack(x-1, ack(x, y-1)) > ack(x, y-1) \qquad (2)$$

by (IH) ($x' \mapsto x-1, y' \mapsto ack(x, y-1)$).

Furthermore, since

$$(\underbrace{x}_{x'}, \underbrace{y-1}_{y'}) <_2 (x, y)$$

then

$$ack(x, y-1) > y-1 \qquad (3)$$

By (1)–(3), we have

$$ack(x, y) \overset{(1)}{=} ack(x-1, ack(x, y-1)) \overset{(2)}{>} ack(x, y-1) \overset{(3)}{>} y-1$$

Hence

$$ack(x, y) > (y-1) + 1 = y$$

Structural Induction

How do we prove properties about logical formulae themselves?

Structural induction principle

To prove a desired property of formulae,

inductive step: Assume the inductive hypothesis, that for arbitrary formula F, the desired property holds for every strict subformula G of F.
Then prove that F has the property.

Since atoms do not have strict subformulae, they are treated as base cases.

Note: "strict subformula relation" is well-founded

Example: Prove that

Every propositional formula F is equivalent to a propositional formula F' constructed with only $\top$, $\vee$, $\neg$ (and propositional variables)

Base cases:

$F : \top \;\Rightarrow\; F' : \top$

$F : \bot \;\Rightarrow\; F' : \neg\top$

$F : P \;\Rightarrow\; F' : P$ for propositional variable P

Inductive step:
Assume as the inductive hypothesis that G, G_1, G_2 are equivalent to G', G_1', G_2' constructed only from $\top$, $\vee$, $\neg$ (and propositional variables).

$$
\begin{array}{lcl}
F : \neg G & \Rightarrow & F' : \neg G' \\
F : G_1 \vee G_2 & \Rightarrow & F' : G_1' \vee G_2' \\
F : G_1 \wedge G_2 & \Rightarrow & F' : \neg(\neg G_1' \vee \neg G_2') \\
F : G_1 \rightarrow G_2 & \Rightarrow & F' : \neg G_1' \vee G_2' \\
F : G_1 \leftrightarrow G_2 & \Rightarrow & (G_1' \rightarrow G_2') \wedge (G_2' \rightarrow G_1') \Rightarrow F' : \ldots
\end{array}
$$

Each F' is equivalent to F and is constructed only by $\top$, $\vee$, $\neg$ by the inductive hypothesis.