

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)

$F[0] \wedge$	... base case
$(\forall n. F[n] \rightarrow F[n+1])$	... inductive step
$\rightarrow \forall x. F[x]$	... 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

- ▶ 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:

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

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

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

$$\begin{aligned} F[n+1] &: 1 + 2 + \dots + n + (n+1) \\ &= \frac{n(n+1)}{2} + (n+1) && (IH) \\ &= \frac{n(n+1) + 2(n+1)}{2} \\ &= \frac{(n+1)(n+2)}{2} \end{aligned}$$

Therefore,

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

Example:

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

$$\blacktriangleright \forall x. x^0 = 1 \quad (E0)$$

$$\blacktriangleright \forall x, y. x^{y+1} = x^y \cdot x \quad (E1)$$

$$\blacktriangleright \forall x, z. \exp_3(x, 0, z) = z \quad (P0)$$

$$\blacktriangleright \forall x, y, z. \exp_3(x, y + 1, z) = \exp_3(x, y, x \cdot z) \quad (P1)$$

($\exp_3(x, y, z)$ stands for $x^y \cdot z$) 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

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

prove

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

$\uparrow$ note

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

$$\exp_3(x', n+1, z') = \exp_3(x', n, x' \cdot z') \quad (\text{P1})$$

$$= x'^n \cdot (x' \cdot z') \quad \text{IH } F[n]; x \mapsto x, z \mapsto x \cdot z'$$

$$= x'^{n+1} \cdot z' \quad (\text{E1})$$

Stepwise Induction (Lists T_{cons})

Axiom schema (induction)

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

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

Note: $\forall \text{ atom } u. F[u]$ 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

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

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

Example: Theory T_{cons}^+ II

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

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

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

Example: Theory T_{cons}^+ III

Reversing a list

$$\blacktriangleright \forall \text{ atom } u. \text{ rvs}(u) = u \quad (\text{R0})$$

$$\blacktriangleright \forall x, y. \text{ rvs}(\text{concat}(x, y)) = \text{concat}(\text{rvs}(y), \text{rvs}(x)) \quad (\text{R1})$$

Example: for atoms a, b, c ,

$$\begin{aligned} & \text{rvs}(\text{cons}(a, \text{cons}(b, c))) && (\text{C0}) \\ = & \text{rvs}(\text{concat}(a, \text{concat}(b, c))) && (\text{C0}) \\ = & \text{concat}(\text{rvs}(\text{concat}(b, c)), \text{rvs}(a)) && (\text{C0}) \\ = & \text{concat}(\text{concat}(\text{rvs}(c), \text{rvs}(b)), \text{rvs}(a)) && (\text{C0}) \\ = & \text{concat}(\text{concat}(c, b), a) && (\text{C0}) \\ = & \text{concat}(\text{cons}(c, b), a) && (\text{C0}) \\ = & \text{cons}(c, \text{concat}(b, a)) && (\text{C0}) \\ = & \text{cons}(c, \text{cons}(b, a)) && (\text{C0}) \end{aligned}$$

Example: Theory T_{cons}^+ IV

Deciding if a list is flat;

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

$$\blacktriangleright \forall \text{ atom } u. \text{flat}(u) \quad (\text{F0})$$

$$\blacktriangleright \forall u, v. \text{flat}(\text{cons}(u, v)) \leftrightarrow \text{atom}(u) \wedge \text{flat}(v) \quad (\text{F1})$$

Example: for atoms a, b, c ,

$$\text{flat}(\text{cons}(a, \text{cons}(b, c))) = \text{true}$$

$$\text{flat}(\text{cons}(\text{cons}(a, b), c)) = \text{false}$$

Prove

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

is T_{cons}^+ -valid.

Base case: For arbitrary atom u ,

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

by F and R0.

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

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

and prove

$$F[\text{cons}(u, v)] : \text{flat}(\text{cons}(u, v)) \rightarrow \\ \text{rvs}(\text{rvs}(\text{cons}(u, v))) = \text{cons}(u, v) \quad (*)$$

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

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

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

Case $\text{atom}(u)$

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

by (F1). Now, show

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

Missing steps:

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

Complete Induction (Peano Arithmetic T_{PA})

Axiom schema (complete induction)

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

$$\rightarrow \forall x. F[x] \quad \dots \text{ conclusion}$$

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 $\text{quot}(5, 3) = 1$ and $\text{rem}(5, 3) = 2$

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

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

Prove

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

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

Best proved by complete induction.

Proof of (1)

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

Consider an arbitrary natural number x .

Assume the inductive hypothesis

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

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

Let y be an arbitrary positive integer

Case $x < y$:

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

Case $\neg(x < y)$:

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

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

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

$$s_1 \succ s_2 \succ s_3 \succ \cdots \text{ where } s_i \in S$$

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:

$$7200 > \dots > 217 > \dots > 0 > \dots > -17 > \dots$$

- ▶ 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 $\prec_i$

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

Construct

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

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

Define lexicographic relation $\prec$ over S as

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

for $s_i, t_i \in S_i$.

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

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

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

$$\begin{aligned} n &\Rightarrow \text{tuple } \bar{n} = (n_1, \dots, n_m) & x &\Rightarrow \text{tuple } \bar{x} = (x_1, \dots, x_m) \\ n' &\Rightarrow \text{tuple } \bar{n}' = (n'_1, \dots, n'_m) \end{aligned}$$

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.

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

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

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

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

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

Example: Ackermann function

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

Ackermann axioms:

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

Ackermann function grows quickly:

$$\text{ack}(0, 0) = 1$$

$$\text{ack}(1, 1) = 3$$

$$\text{ack}(2, 2) = 7$$

$$\text{ack}(3, 3) = 61$$

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

Proof of termination

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

$$(L0) \quad \forall y. \text{ack}(0, y) = y + 1$$

does not involve recursive call

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

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

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

Proof of property

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

$$\forall x, y. \text{ack}(x, y) > y$$

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

Consider arbitrary natural numbers x, y .

Assume the inductive hypothesis

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

Show

$$F[x, y] : \text{ack}(x, y) > y.$$

Case $x = 0$:

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

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

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

Since

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

Then

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

Thus

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

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

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

Since

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

Then

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

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

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

By (1)–(3), we have

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

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:

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

$$F : \perp \Rightarrow F' : \neg\top$$

$$F : P \Rightarrow F' : P \quad \text{for propositional variable } P$$

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).

$$F : \neg G \quad \Rightarrow \quad F' : \neg G'$$

$$F : G_1 \vee G_2 \quad \Rightarrow \quad F' : G'_1 \vee G'_2$$

$$F : G_1 \wedge G_2 \quad \Rightarrow \quad F' : \neg(\neg G'_1 \vee \neg G'_2)$$

$$F : G_1 \rightarrow G_2 \quad \Rightarrow \quad F' : \neg G'_1 \vee G'_2$$

$$F : G_1 \leftrightarrow G_2 \quad \Rightarrow \quad (G'_1 \rightarrow G'_2) \wedge (G'_2 \rightarrow G'_1) \Rightarrow F' : \dots$$

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