

HW 3 is out on webpage
(usual Friday deadline).

Inference Proof

CSE 311 Fall 23
Lecture 9

A Brief Return to Training Wheels

For about 1.5 lectures, we're going to study "inference proofs"

The rules for these proofs are

1. Strict enough that computers can check them (there are languages designed to do that!)
2. More general than the simplification rules we've seen so far.
You'll still use the simplification rules!
But you'll find we can prove more things (at least without significant difficulty).
3. More similar to the proofs we spend most of the quarter writing.

A Brief Return to Training Wheels

The claims and proofs are quite abstract!

Why spend time here?

Some computer scientists use the fully formal (computer-checkable) version of the rules.

Our PL group here contains experts in these topics!

We want your takeaways to be

In principle, any proof we write in this class could be made fully formal and checked.

But it can be a lot of work, so we usually think and communicate in English. We're people after all!

Inference Proofs

A new way of thinking of proofs:

Here's one way to get an iron-clad guarantee:

1. Write down all the facts we know.
2. Combine the things we know to derive new facts.
3. Continue until what we want to show is a fact.

Drawing Conclusions

You know "If it is raining, then I have my umbrella"

And "It is raining"

You should conclude.... I have my umbrella!

For whatever you conclude, convert the statement to propositional logic – will your statement hold for any propositions, or is it specific to raining and umbrellas?

I know $(p \rightarrow q)$ and p , I can conclude q

Or said another way: $[(p \rightarrow q) \wedge p] \rightarrow q$

Modus Ponens

The inference from the last slide is always valid. I.e.

$$[(p \rightarrow q) \wedge p] \rightarrow q$$

Has only True rows in its truth table (it's a tautology)

Modus Ponens – a formal proof

$[(p \rightarrow q) \wedge p] \rightarrow q$	\equiv	$[(\neg p \vee q) \wedge p] \rightarrow q$	Law of Implication
	\equiv	$[p \wedge (\neg p \vee q)] \rightarrow q$	Commutativity
	\equiv	$[(p \wedge \neg p) \vee (p \wedge q)] \rightarrow q$	Distributivity
	\equiv	$[F \vee (p \wedge q)] \rightarrow q$	Negation
	\equiv	$[(p \wedge q) \vee F] \rightarrow q$	Commutativity
	\equiv	$[(p \wedge q)] \rightarrow q$	Identity
	\equiv	$[\neg(p \wedge q)] \vee q$	Law of Implication
	\equiv	$[\neg p \vee \neg q] \vee q$	DeMorgan's Law
	\equiv	$\neg p \vee [\neg q \vee q]$	Associativity
	\equiv	$\neg p \vee [q \vee \neg q]$	Commutativity
	\equiv	$\neg p \vee T$	Negation
	\equiv	T	Domination

Modus Ponens

The inference from the last slide is always valid. I.e.

$$[(p \rightarrow q) \wedge p] \rightarrow q \equiv \text{T}$$

We use that inference A LOT

So often people gave it a name ("Modus Ponens")

So often...we don't have time to repeat that 12 line proof EVERY TIME.

Let's make this another law we can apply in a single step.

Just like refactoring a method in code.

Notation – Laws of Inference

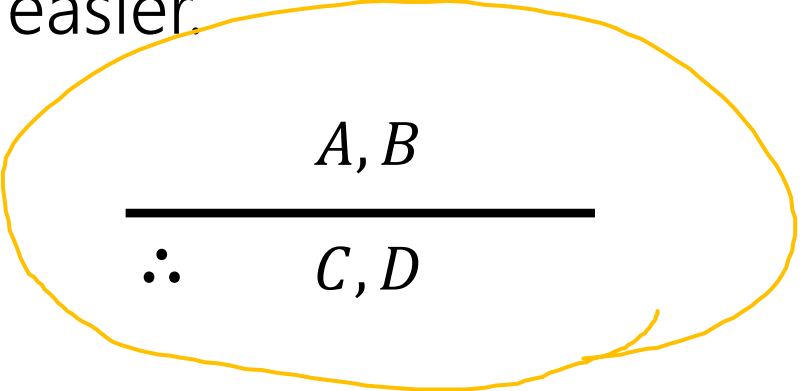
We're using the " \rightarrow " symbol A LOT.

Too much

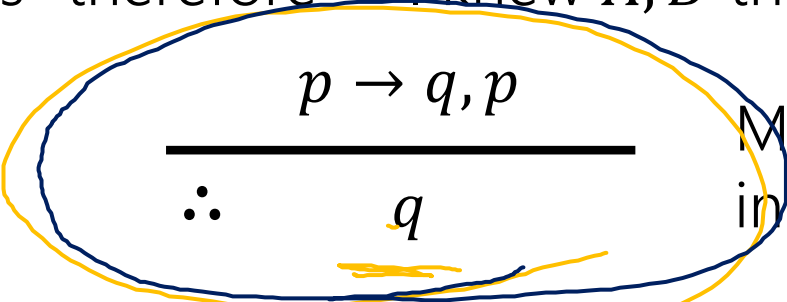
Some new notation to make our lives easier.

If we know **both** A and B

\therefore We can conclude any (or all) of C, D


$$\frac{A, B}{\therefore C, D}$$

" \therefore " means "therefore" – I knew A, B therefore I can conclude C, D .


$$\frac{p \rightarrow q, p}{\therefore q}$$

Modus Ponens, i.e. $[(p \rightarrow q) \wedge p] \rightarrow q$,
in our new notation.

Another Proof

Let's keep going.

I know "If it is raining then I have my umbrella" and "I do not have my umbrella"

I can conclude... It is not raining!

What's the general form? $[(p \rightarrow q) \wedge \neg q] \rightarrow \neg p$

How do you think the proof will go?

If you had to convince a friend of this claim in English, how would you do it?

A proof!

We know $p \rightarrow q$ and $\neg q$; we want to conclude $\neg p$.

Let's try to prove it. Our goal is to list facts until our goal becomes a fact.

We'll number our facts, and put a justification for each new one.

A proof!

We know $p \rightarrow q$ and $\neg q$; we want to conclude $\neg p$.

Let's try to prove it. Our goal is to list facts until our goal becomes a fact.

We'll number our facts, and put a justification for each new one.

1. $p \rightarrow q$ Given
2. $\neg q$ Given
3. $\neg q \rightarrow \neg p$ Contrapositive of 1.
4. $\neg p$ Modus Ponens on 3,2.

Try it yourselves

Suppose you know $p \rightarrow q$, $\neg s \rightarrow \neg q$, and p .
Give an argument to conclude s .

1. $p \rightarrow q$ Given
2. $\neg s \rightarrow \neg q$ Given
3. p Given
4. q Modus Ponens (1, 3)
5. $q \rightarrow s$ Contrapositive (2)
6. s MP (4, 5)

~~Pollev.com/robbie~~

~~Help me adjust my explanation!~~

Try it yourselves

Suppose you know $p \rightarrow q$, $\neg s \rightarrow \neg q$, and p .
Give an argument to conclude s .

- | | | |
|----|-----------------------------|---------------------|
| 1. | $p \rightarrow q$ | Given |
| 2. | $\neg s \rightarrow \neg q$ | Given |
| 3. | p | Given |
| 4. | q | Modus Ponens 1,3 |
| 5. | $q \rightarrow s$ | Contrapositive of 2 |
| 6. | s | Modus Ponens 5,4 |

That was abstract!

Imagine that instead someone had said:

If `next` is `null`, then we go down the else-branch

If the input list is non-empty, then we don't go down the else-branch.

This test uses a non-empty list as input.

Can you conclude anything?

So...why do the abstract proof?

Mostly to practice...

Though sometimes it's helpful to make things abstract.

The more general you make a claim...

The more abstract it is, and therefore more difficult to understand on the surface...

But the more different contexts it can be used in.

More Inference Rules

We need a couple more inference rules.

These rules set us up to get facts in exactly the right form to apply the really useful rules.

A lot like commutativity and associativity in the propositional logic rules.

Eliminate \wedge	$A \wedge B$	I know the fact $A \wedge B$
	$\therefore A, B$	\therefore I can conclude A is a fact and B is a fact separately .

More Inference Rules

In total, we have two for \wedge and two for \vee , one to create the connector, and one to remove it.

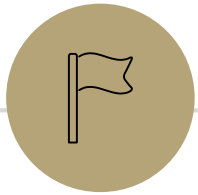
$$\boxed{\text{Eliminate } \wedge} \frac{A \wedge B}{\therefore A, B}$$

$$\boxed{\text{Intro } \wedge} \frac{A, B}{\therefore A \wedge B}$$

$$\boxed{\text{Eliminate } \vee} \frac{A \vee B, \neg A}{\therefore B}$$

$$\boxed{\text{Intro } \vee} \frac{A}{\therefore A \vee B, B \vee A}$$

None of these rules are surprising, but they are useful.



Direct Proof Rule



The Direct Proof Rule

We've been implicitly using another "rule" in our English proofs, the direct proof rule

Write a proof "given A conclude B "

 $A \rightarrow B$

Direct Proof
rule -----
 $A \Rightarrow B$
 $A \rightarrow B$

This rule is different from the others – $A \Rightarrow B$ is not a "single fact."

It's an observation that we've done a proof. (i.e. that we showed fact B starting from A .)

We will get a lot of mileage out of this rule.

Inference Rules

Eliminate \wedge

$$\frac{A \wedge B}{\therefore A, B}$$

Eliminate \vee

$$\frac{A \vee B, \neg A}{\therefore B}$$

Intro \wedge

$$\frac{A, B}{\therefore A \wedge B}$$

Intro \vee

$$\frac{A}{\therefore A \vee B, B \vee A}$$

Direct Proof
rule

$$\frac{A \Rightarrow B}{A \rightarrow B}$$

Modus
Ponens

$$\frac{P \rightarrow Q, P}{\therefore Q}$$

You can still use all the propositional logic equivalences too!

The Direct Proof Rule

We've been implicitly using another "rule" today, the direct proof rule

Write a proof "given A conclude B "

$A \rightarrow B$

Direct Proof
rule

$A \Rightarrow B$
 $A \rightarrow B$

This rule is different from the others – $A \Rightarrow B$ is not a "single fact."
It's an observation that we've done a proof. (i.e. that we showed fact B starting from A .)

We will get a lot of mileage out of this rule...starting right now.

How would you argue...

Let's say you have a piece of code.

And you think if the code gets null input then a NullPointerException will be thrown.

How would you convince your friend?

You'd probably trace the code, assuming you would get null input.

The code was your **given**

The null input is an assumption

In general

How do you convince someone that $p \rightarrow q$ is true given some surrounding context/some surrounding givens?

You suppose p is true (you assume p)

And then you'll show q must also be true.
Just from p and the Given information.

The Direct Proof Rule

Write a proof "assume A conclude B "

$A \rightarrow B$

Direct Proof
rule

$A \Rightarrow B$
 $A \rightarrow B$

This rule is different from the others – $A \Rightarrow B$ is not a "single fact."
It's an observation that we've done a proof. (i.e. that we showed fact B starting from A .)

We will get a lot of mileage out of this rule...starting today!

Given: $((p \rightarrow q) \wedge (q \rightarrow r))$ ←

Show: $(p \rightarrow r)$

Here's an incorrect proof.

- | | |
|---|------------------------|
| 1. $(p \rightarrow q) \wedge (q \rightarrow r)$ | Given |
| 2. $p \rightarrow q$ | Eliminate \wedge (1) |
| 3. $q \rightarrow r$ | Eliminate \wedge (1) |
| 4. p | Given??? |
| 5. q | Modus Ponens 4,2 |
| 6. r | Modus Ponens 5,3 |
| 7. $p \rightarrow r$ | Direct Proof Rule |

Given: $((p \rightarrow q) \wedge (q \rightarrow r))$
Show: $(p \rightarrow r)$

Here's an incorrect proof.

1. $(p \rightarrow q) \wedge (q \rightarrow r)$

2. $p \rightarrow q$

3. $q \rightarrow r$

4. p

5. q

6. r

7. $p \rightarrow r$

Eliminate \wedge (1)

Given ?????

Modus Ponens 4,2

Modus Ponens 5,3

Direct Proof Rule

Proofs are supposed to be lists of facts.
Some of these "facts" aren't really facts...

These facts depend on p .
But p isn't known generally.
It was assumed for the
purpose of proving $p \rightarrow r$.

Given: $((p \rightarrow q) \wedge (q \rightarrow r))$
Show: $(p \rightarrow r)$

Here's an incorrect proof.

1. $(p \rightarrow q) \wedge (q \rightarrow r)$

2. $p \rightarrow q$

3. $q \rightarrow r$

4. p

5. q

6. r

7. $p \rightarrow r$

Proofs are supposed to be lists of facts.
Some of these "facts" aren't really facts...

Eliminate \wedge (1)

Given ?????

Modus Ponens 4,2

Modus Ponens 5,3

Direct Proof Rule

These facts depend on p .
But p isn't known generally.
It was assumed for the
purpose of proving $p \rightarrow r$.

Given: $((p \rightarrow q) \wedge (q \rightarrow r))$

Show: $(p \rightarrow r)$

Here's a corrected version of the proof.

1. $(p \rightarrow q) \wedge (q \rightarrow r)$

2. $p \rightarrow q$

3. $q \rightarrow r$

4.1 p

4.2 q

4.3 r

5. $p \rightarrow r$

Given

Eliminate \wedge 1

Eliminate \wedge 1

Assumption

Modus Ponens 4.1,2

Modus Ponens 4.2,3

Direct Proof Rule

When introducing an assumption to prove an implication: Indent, and change numbering.

When reached your conclusion, use the Direct Proof Rule to observe the implication is a fact.

The conclusion is an unconditional fact (doesn't depend on p) so it goes back up a level

Try it!

Given: $p \vee q, (r \wedge s) \rightarrow \neg q, r$.
Show: $s \rightarrow p$

$$\text{Eliminate } \wedge \frac{A \wedge B}{\therefore A, B}$$

$$\text{Eliminate } \vee \frac{A \vee B, \neg A}{\therefore B}$$

$$\text{Intro } \wedge \frac{A; B}{\therefore A \wedge B}$$

$$\text{Intro } \vee \frac{A}{\therefore A \vee B, B \vee A}$$

$$\text{Direct Proof rule} \frac{A \Rightarrow B}{A \rightarrow B}$$

$$\text{Modus Ponens} \frac{P \rightarrow Q; P}{\therefore Q}$$

You can still use all the propositional logic equivalences too!

Try it!

Given: $p \vee q, (r \wedge s) \rightarrow \neg q, r$.

Show: $s \rightarrow p$

1. $p \vee q$ Given
2. $(r \wedge s) \rightarrow \neg q$ Given
3. r Given
 - 4.1 s Assumption
 - 4.2 $r \wedge s$ Intro \wedge (3,4.1)
 - 4.3 $\neg q$ Modus Ponens (2, 4.2)
 - 4.4 $q \vee p$ Commutativity (1)
 - 4.5 p Eliminate \vee (4.4, 4.3)
5. $s \rightarrow p$ Direct Proof Rule



Inference Proofs in Predicate Logic

Proofs with Quantifiers

We've done symbolic proofs with propositional logic.

To include predicate logic, we'll need some rules about how to use quantifiers.

$$\boxed{\text{Eliminate } \forall} \frac{\forall x P(x)}{\therefore \underline{P(a)} \text{ for any } a}$$

$$\boxed{\text{Intro } \exists} \frac{P(c) \text{ for some } c}{\therefore \underline{\exists x P(x)}}$$

$$\boxed{\text{Intro } \forall} \frac{\underline{P(a)}; a \text{ is } \underline{\text{arbitrary}}}{\therefore \underline{\forall x P(x)}}$$

$$\boxed{\text{Eliminate } \exists} \frac{\exists x P(x)}{\therefore P(c) \text{ for a } \underline{\text{fresh } c}}$$

Let's see a good example, then come back to those "arbitrary" and "fresh" conditions.

Proof Using Quantifiers

Suppose we know $\exists x P(x)$ and $\forall y [P(y) \rightarrow Q(y)]$. Conclude $\exists x Q(x)$.

Eliminate \forall $\frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$

Intro \exists $\frac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$

Intro \forall $\frac{P(a); a \text{ is arbitrary}}{\therefore \forall x P(x)}$

Eliminate \exists $\frac{\exists x P(x)}{\therefore P(c) \text{ for a fresh } c}$

Proof Using Quantifiers

Suppose we know $\exists x P(x)$ and $\forall y [P(y) \rightarrow Q(y)]$. Conclude $\exists x Q(x)$.

$$\boxed{\text{Intro } \exists} \frac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$$

$$\boxed{\text{Eliminate } \exists} \frac{\exists x P(x)}{\therefore P(c) \text{ for a fresh } c}$$

$$\boxed{\text{Eliminate } \forall} \frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$$

$$\boxed{\text{Intro } \forall} \frac{P(a); a \text{ is arbitrary}}{\therefore \forall x P(x)}$$

Proof Using Quantifiers

$P(x)$ prime(x)
 $Q(x)$ odd or eq 2 (x)

Suppose we know $\exists xP(x)$ and $\forall y[P(y) \rightarrow Q(y)]$. Conclude $\exists xQ(x)$.

- $\exists xP(x)$
- $P(a)$
- $\forall y[P(y) \rightarrow Q(y)]$
- $P(a) \rightarrow Q(a)$
- $Q(a)$
- $\exists xQ(x)$

Given
Eliminate \exists (1)
Given
Eliminate \forall (3)
Modus Ponens 2,4
Intro \exists 5

Intro \exists $\frac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$

Eliminate \exists $\frac{\exists x P(x)}{\therefore P(c) \text{ for a fresh } c}$

Eliminate \forall $\frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$
 \rightarrow
 $P(a); a$ is arbitrary

Intro \forall $\frac{P(a); a \text{ is arbitrary}}{\therefore \forall x P(x)}$

Proofs with Quantifiers

We've done symbolic proofs with propositional logic.

To include predicate logic, we'll need some rules about how to use quantifiers.

$$\boxed{\text{Eliminate } \forall} \frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$$

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$$\boxed{\text{Intro } \forall} \frac{P(a); a \text{ is arbitrary}}{\therefore \forall x P(x)}$$

$$\boxed{\text{Eliminate } \exists} \frac{\exists x P(x)}{\therefore P(c) \text{ for a fresh } c}$$

"arbitrary" means a is "just" a variable in our domain. It doesn't depend on any other variables and wasn't introduced with other information.

Proofs with Quantifiers

We've done symbolic proofs with propositional logic.

To include predicate logic, we'll need some rules about how to use quantifiers.

$$\boxed{\text{Eliminate } \forall} \frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$$

$$\boxed{\text{Intro } \exists} \frac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$$

$$\boxed{\text{Intro } \forall} \frac{P(a); a \text{ is arbitrary}}{\therefore \forall x P(x)}$$

$$\boxed{\text{Eliminate } \exists} \frac{\exists x P(x)}{\therefore P(c) \text{ for a fresh } c}$$

"fresh" means c is a new symbol (there isn't another c somewhere else in our proof).

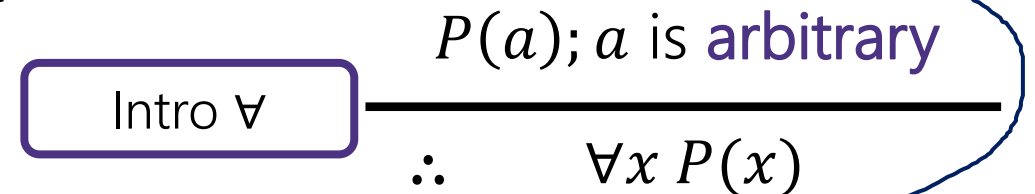
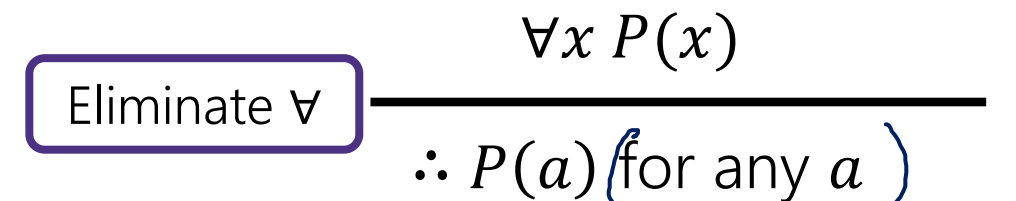
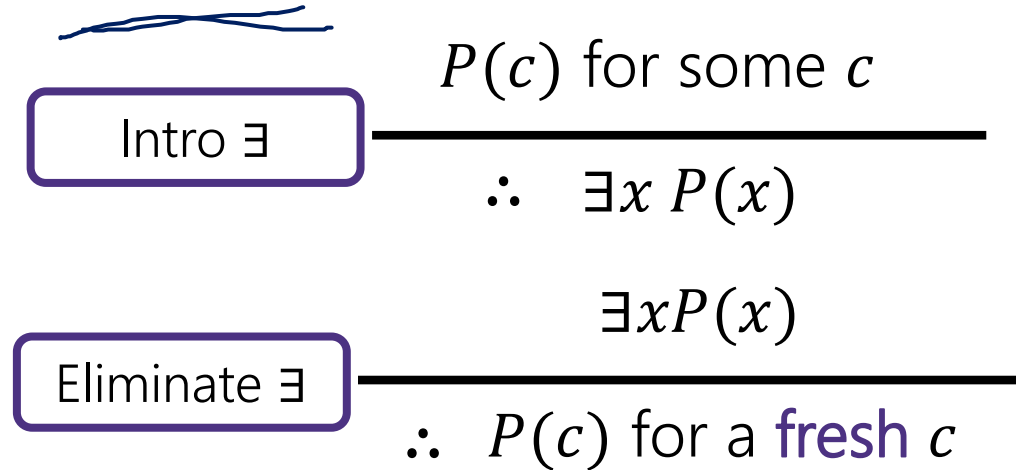
Fresh and Arbitrary

Suppose we know $\exists x P(x)$. Can we conclude $\forall x P(x)$?

1. $\exists x P(x)$ Given
2. $P(a)$ Eliminate \exists (1)
3. $\forall x P(x)$ Intro \forall (2)

This proof is **definitely** wrong.
(take $P(x)$ to be "is a prime number")

a wasn't **arbitrary**. We knew something about it – it's the x that exists to make $P(x)$ true.



Fresh and Arbitrary

$$\boxed{\text{Intro } \forall} \frac{P(a); a \text{ is } \underline{\text{arbitrary}}}{\therefore \forall x P(x)}$$

$$\boxed{\text{Eliminate } \exists} \frac{\exists x P(x)}{\therefore P(c) \text{ for a } \underline{\text{fresh}} c}$$

You can trust a variable to be **arbitrary** if you introduce it as such. If you eliminated a \forall to create a variable, that variable is arbitrary. Otherwise it's not arbitrary – it depends on something.

You can trust a variable to be **fresh** if the variable doesn't appear anywhere else (i.e. just use a new letter)

Fresh and Arbitrary

$$\boxed{\text{Eliminate } \forall} \frac{\forall x P(x)}{\therefore P(a) \text{ for any } a}$$

$$\boxed{\text{Intro } \exists} \frac{P(c) \text{ for some } c}{\therefore \exists x P(x)}$$

There are no similar concerns with these two rules.

Want to reuse a variable when you eliminate \forall ? Go ahead.

Have a c that depends on many other variables, and want to intro \exists ?

Also not a problem.

Arbitrary

In section, you said: $[\exists y \forall x P(x, y)] \rightarrow [\forall x \exists y P(x, y)]$. Let's prove it!!

Arbitrary

In section, you said: $[\exists y \forall x P(x, y)] \rightarrow [\forall x \exists y P(x, y)]$. Let's prove it!!

- | | |
|--|-----------------------|
| 1.1 $\exists y \forall x P(x, y)$ | Assumption |
| 1.2 $\forall x P(x, c)$ | Elim \exists (1.1) |
| 1.3 Let a be arbitrary. | -- |
| 1.4 $P(a, c)$ | Elim \forall (1.2) |
| 1.5 $\exists y P(a, y)$ | Intro \exists (1.4) |
| 1.6 $\forall x \exists y P(x, y)$ | Intro \forall (1.5) |
| 2. $[\exists y \forall x P(x, y)] \rightarrow [\forall x \exists y P(x, y)]$ | Direct Proof Rule |

Arbitrary

In section, you said: $[\exists y \forall x P(x, y)] \rightarrow [\forall x \exists y P(x, y)]$. Let's prove it!!

1.1 $\exists y \forall x P(x, y)$ Assumption

1.2 $\forall x P(x, c)$ Elim \exists (1.1)

1.4 $P(a, c)$ Elim \forall (1.2)

1.5 $\exists y P(a, y)$ Intro \exists (1.4)

1.6 $\forall x \exists y P(x, y)$ Intro \forall (1.5)

2. $[\exists y \forall x P(x, y)] \rightarrow [\forall x \exists y P(x, y)]$ Direct Proof Rule

It is not required to have “variable is arbitrary” as a step before using it. But many people (including Robbie) find it helpful.

Find The Bug

Let your domain of discourse be integers.

We claim that given $\forall x \exists y \text{ Greater}(y, x)$, we can conclude $\exists y \forall x \text{ Greater}(y, x)$

Where $\text{Greater}(y, x)$ means $y > x$

1. $\forall x \exists y \text{ Greater}(y, x)$ Given
2. Let a be an arbitrary integer --
3. $\exists y \text{ Greater}(y, a)$ Elim \forall (1)
4. $\text{Greater}(b, a)$ Elim \exists (2)
5. $\forall x \text{ Greater}(b, x)$ Intro \forall (4)
6. $\exists y \forall x \text{ Greater}(y, x)$ Intro \exists (5)

$$b = a + 1$$

Find The Bug

1. $\forall x \exists y \text{ Greater}(y, x)$ Given
2. Let a be an arbitrary integer --
3. $\exists y \text{ Greater}(y, a)$ Elim \forall (1)
4. $\text{Greater}(b, a)$ Elim \exists (2)
5. $\forall x \text{ Greater}(b, x)$ Intro \forall (4)
6. $\exists y \forall x \text{ Greater}(y, x)$ Intro \exists (5)

b is not a single number! The variable b depends on a . You can't get rid of a while b is still around.

What is b ? It's probably something like $a + 1$.

Bug Found

There's one other "hidden" requirement to introduce \forall .

"No other variable in the statement can depend on the variable to be generalized"

Think of it like this -- b was probably $a + 1$ in that example.

You wouldn't have generalized from `Greater($a + 1, a$)`

To $\forall x$ `Greater($a + 1, x$)`. There's still an a , you'd have replaced all the a 's.

x depends on y if y is in a statement when x is introduced.

This issue is much clearer in English proofs, which we'll start next time.



Extra Practice



Caution

Be careful! Logical inference rules can only be applied to **entire** facts. They cannot be applied to portions of a statement (the way our propositional rules could). Why not?

Suppose we know $p \rightarrow q, r$. Can we conclude q ?

1. $p \rightarrow q$ Given
2. r Given
3. $(p \vee r) \rightarrow q$ Introduce \vee (1)
4. $p \vee r$ Introduce \vee (2)
5. q Modus Ponens 3,4.

$$\boxed{\text{Intro } \vee} \frac{A}{\therefore A \vee B, B \vee A}$$

One more Proof

Show if we know: $p, q, [(p \wedge q) \rightarrow (r \wedge s)], r \rightarrow t$ we can conclude t .

One more Proof

Show if we know: $p, q, [(p \wedge q) \rightarrow (r \wedge s)], r \rightarrow t$ we can conclude t .

1. p Given
2. q Given
3. $[(p \wedge q) \rightarrow (r \wedge s)]$ Given
4. $r \rightarrow t$ Given
5. $p \wedge q$ Intro \wedge (1,2)
6. $r \wedge s$ Modus Ponens (3,5)
7. r Eliminate \wedge (6)
8. t Modus Ponens (4,7)