

\mathcal{A} : THE LOGIC OF All x are y

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Probably the key point of logic is that there is a distinction between

syntax and **semantics**.

The idea is that syntax is the raw symbols.

The semantics is where we get the meaning.

So in our examples, we need some **context** or **model** to give a meaning.

In our examples, the syntax will start with some set **N** of **nouns** p, q, n, n_1, \dots

Then our **sentences** are expressions of the form *All p are q .*

Syntax: We start with N , and then we make sentences *All p are q* ,

We do not use any of the traditional logic symbols $\wedge, \vee, \neg, \forall, \exists$.
These could be added, however.

We use Greek letters φ, ψ, χ , etc. for sentences:

Syntax: We start with N , and then we make sentences *All p are q* ,

Semantics: A model \mathcal{M} is a set M ,
and for each noun p we have an **interpretation** $\llbracket p \rrbracket \subseteq M$.

$$\mathcal{M} \models \textit{All } p \textit{ are } q \quad \text{iff} \quad \llbracket p \rrbracket \subseteq \llbracket q \rrbracket$$

The symbols $\mathcal{M} \models \varphi$ is read as \mathcal{M} **satisfies** φ .

A statement like $\mathcal{M} \models \textit{All } p \textit{ are } q$ could also be read as

All p are q is true in \mathcal{M}

One fine point on the definition is that if $\llbracket x \rrbracket$ is the empty set \emptyset , then our sentence *All x are y* is *true*!

So in this room now,

All people in the room over 7 feet tall are standing

is (on this definition) true.

This strange point will lead us to various issues over the week.

For now, it might be best to say that it's true because there are *no exceptions*.

But we again admit that our semantics of *All x are y* is not what most people would agree to in cases where $\llbracket x \rrbracket = \emptyset$.

ANOTHER FINE POINT: WHAT IS THIS N ?

The name of our logic is \mathcal{A} , standing for *All*.

Recall that \mathcal{A} is built from a set N of nouns.

This set could be anything.

In examples from English, it would be common nouns, usually in the plural.

In a more mathematical setting, we would usually take it to be some set of Roman letters (with subscripts if we need them).

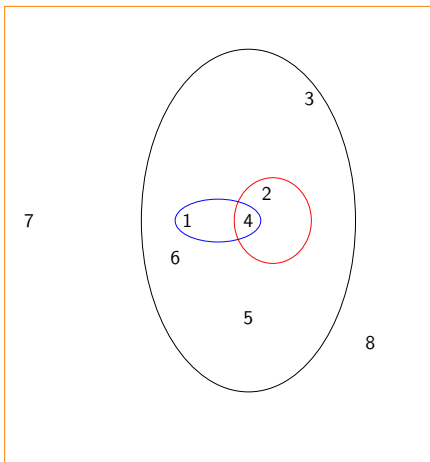
PRACTICE WITH SUBSETS AND WITH MODELS

Let $M = \{1, 2, 3, 4, 5, 6, 7, 8\}$: the orange rectangle.

Let $\llbracket a \rrbracket = \{1, 2, 3, 4, 5, 6\}$, in the black oval.

Let $\llbracket x \rrbracket = \{1, 4\}$, shown in the blue oval.

Let $\llbracket y \rrbracket = \{2, 4\}$, in the red oval.



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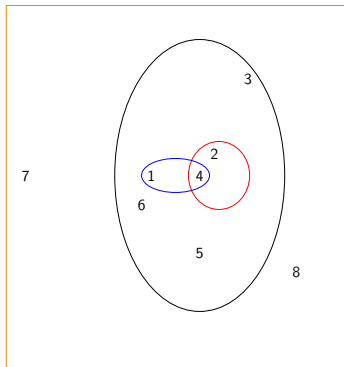
$\mathcal{M} \models \text{All } x \text{ are } a$

$\mathcal{M} \not\models \text{All } a \text{ are } x$

$\mathcal{M} \not\models \text{All } y \text{ are } x$

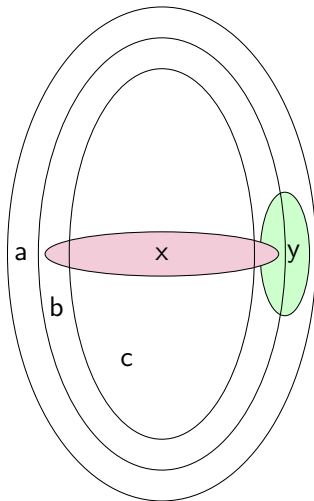
$\mathcal{M} \models \text{All } y \text{ are } a$

$\mathcal{M} \models \text{All } a \text{ are } a$



MORE PRACTICE WITH SUBSETS AND WITH MODELS

My convention is that each letter represents the **biggest** region that it is in.



MORE PRACTICE WITH SUBSETS AND WITH MODELS

$c \subseteq b$ and $b \subseteq a$

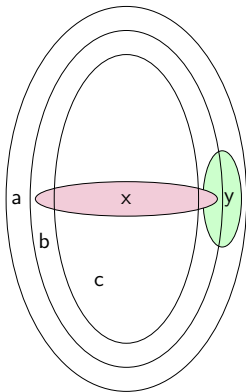
$c \subseteq a$ (but this **follows**)

For all sets q in the picture, $q \subseteq q$ (again, this is by **logic**).

$y \subseteq a$

$x \subseteq b$

No other inclusion relations hold.



$$\varphi_1, \dots, \varphi_n \models \psi$$

$\varphi_1, \dots, \varphi_n \models \psi$ MEANS

Every model of the premises $\varphi_1, \dots, \varphi_n$ is a model of the conclusion ψ .

We read this as ψ **follows from** $\varphi_1, \dots, \varphi_n$.

To argue that $\varphi_1, \dots, \varphi_n \models \psi$ we need some reasoning.

Usually, we do this in English and in an informal way, just as one would do ordinary mathematics.

$$\varphi_1, \dots, \varphi_n \not\models \psi$$

$\varphi_1, \dots, \varphi_n \models \psi$ MEANS

Every model of the premises $\varphi_1, \dots, \varphi_n$ is a model of the conclusion ψ .

$\varphi_1, \dots, \varphi_n \not\models \psi$ MEANS

Some model of the premises $\varphi_1, \dots, \varphi_n$ is **not** a model of the conclusion ψ .

To argue that $\varphi_1, \dots, \varphi_n \not\models \psi$ we can produce a **counterexample**.

The main thing is that we have a rigorous definition.

$\text{ALL } x \text{ ARE } y, \text{ALL } y \text{ ARE } z \models \text{ALL } x \text{ ARE } z$

This means:

Every model \mathcal{M} of the two premises

$$\varphi_1 = \text{All } x \text{ are } y$$

$$\varphi_2 = \text{All } y \text{ are } z$$

is also a model of the conclusion $\psi = \text{All } x \text{ are } z$.

ALL x ARE y , ALL y ARE $z \models$ ALL x ARE z

Here is the reasoning:

Let \mathcal{M} be any model, and assume that the premises are true in \mathcal{M} .
We show that the conclusion is also true in \mathcal{M} .

So we know that $\llbracket x \rrbracket \subseteq \llbracket y \rrbracket$, and also $\llbracket y \rrbracket \subseteq \llbracket z \rrbracket$.
Thus by basic facts about sets, $\llbracket x \rrbracket \subseteq \llbracket z \rrbracket$.

This shows that $\mathcal{M} \models$ All x are z .

And since \mathcal{M} was arbitrary, we are done.

ALL x ARE y , ALL y ARE $z \not\models$ ALL z ARE x

This means:

There is **some** model \mathcal{M} of the two premises

$$\varphi_1 = \text{All } x \text{ are } y$$

$$\varphi_2 = \text{All } y \text{ are } z$$

which is **not** a model of the conclusion $\psi = \text{All } z \text{ are } x$.

ALL x ARE y , ALL y ARE z $\not\models$ ALL z ARE x

We have to give a concrete counterexample.

Let's take $M = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$,

$\llbracket x \rrbracket = \{1, 2, 3, 4\}$,

$\llbracket y \rrbracket = \{1, 2, 3, 4, 5, 9\}$,

$\llbracket z \rrbracket = \{1, 2, 3, 4, 5, 7, 9\}$.

Then the premises are true in this model,
but the conclusion is false.

(Any model would do, I picked a “random” one.)

So we are done.

A SMALL NOTE ON NOTATION

Throughout the week, we'll use letters like φ, ψ, χ for **sentences**.

We use letters like Γ (Greek letter Gamma) for **sets of sentences**.

And then we would write $\Gamma \models \varphi$ to mean
that every model of all the sentences in Γ is also a model of φ .

However, if Γ is a set that we have listed out, say

$$\Gamma = \{\varphi_1, \varphi_2, \dots, \varphi_{104}\}$$

Then usually we would write $\Gamma \models \varphi$ as

$$\varphi_1, \varphi_2, \dots, \varphi_{104} \models \varphi$$

rather than as

$$\{\varphi_1, \varphi_2, \dots, \varphi_{104}\} \models \varphi.$$

That is, we drop the set braces on the left of the \models symbol.
We do this to make things a little more readable.

$$\overbrace{\varphi_1, \varphi_2, \dots, \varphi_n}^{\text{premises}} \models \overbrace{\varphi}^{\text{conclusion}}$$

The intuition is that

$$\varphi_1, \varphi_2, \dots, \varphi_n \models \varphi$$

should mean that

any circumstance in which the premises $\varphi_1, \varphi_2, \dots, \varphi_n$ are all true is also a circumstance in which the conclusion φ is true

Of course, the “official” meaning is in terms of models.

FORMAL PROOFS: A PRELIMINARY POINT

A formal proof is like a **caricature** of human reasoning.

It is very common in introductory logic classes to present one or another kind of formal proof systems.
(There are probably hundreds of them.)

Working with a formal proof system is usually a tedious and boring experience.

PROOF TREES FOR OUR LANGUAGE \mathcal{A}

Let Γ be a set of sentences $\{\varphi_1, \dots, \varphi_n\}$.

A **proof tree over Γ** is a tree following properties:

- ① The leaves are either labeled with sentences from Γ , or with sentences of the form *All x are x* .
- ② The interior leaves match one of the rules of our system (see the next slide).

The trees are drawn with the **root** at the bottom and the **leaves** at the top.

$\Gamma \vdash \varphi$ MEANS

There is a proof tree over Γ whose root is labeled φ .

This is read “ Γ **proves** φ .”

or “there is a **proof of φ from Γ ,**”

or “ **φ is provable from Γ** ”.

THE RULES FOR BUILDING TREES

$$\frac{}{\text{All } p \text{ are } p} \text{ AXIOM}$$

$$\frac{\text{All } p \text{ are } n \quad \text{All } n \text{ are } q}{\text{All } p \text{ are } q} \text{ BARBARA}$$

The (AXIOM) rule means that we can have All p are p provided that there is **nothing above it**, and this All p are p is justified as an “axiom”.

The second rule is pretty straightforward.

Let Γ be the set

$\{All\ a\ are\ b, All\ q\ are\ a, All\ b\ are\ d, All\ c\ are\ d, All\ a\ are\ q\}$

Let φ be $All\ q\ are\ d$.

EXAMPLE

Here is a proof tree showing that $\Gamma \vdash \varphi$:

$$\frac{All\ q\ are\ a \quad \frac{All\ a\ are\ b \quad All\ b\ are\ d}{All\ a\ are\ d} \text{ BARBARA}}{All\ q\ are\ d} \text{ BARBARA}$$

All three leaves belong to Γ .

Note also that two elements of Γ are not used as leaves.

This is permitted according to our definition.

The proof tree above shows that $\Gamma \vdash \varphi$.

WHAT ARE WE DOING HERE?

The idea is that **proof trees** are our model of **basic reasoning** using the very limited kind of sentences that we have in this lecture:

All x are y.

It can be examined (and even constructed) by a person or computer who has no understanding of anything but the rules!

There are several hopes about this work:

- ★ The whole thing will “scale up” to include many more words. (This would call on **linguistic semantics** to provide the correct notion of **model**.)
- ★ The formal relation \vdash should have something to do with \models (logic)
- ★ The proof system \vdash should have something to do with actual human reasoning (psychology)
- ★ A computer should be able to work with \vdash without understanding anything.

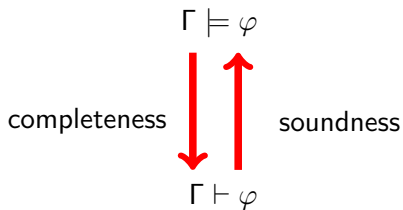
A SET Γ , AND TWO QUESTIONS

$$\Gamma = \left\{ \begin{array}{l} \text{All a are b,} \\ \text{All a are c,} \\ \text{All b are c,} \\ \text{All c are b,} \\ \text{All c are d,} \\ \text{All b are e,} \\ \text{All d are g,} \\ \text{All f are g,} \\ \text{All g are f} \end{array} \right\}$$

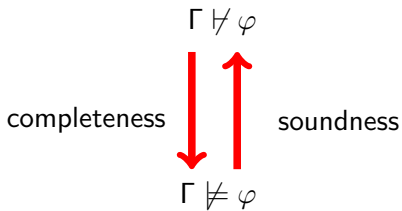
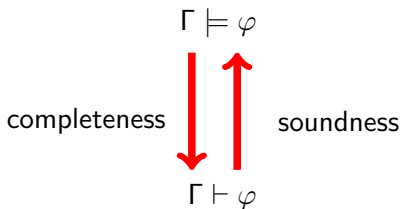
Do you think that $\Gamma \vdash \text{All } b \text{ are } g$?

Do you think that $\Gamma \vdash \text{All } d \text{ are } e$?

SOUNDNESS AND COMPLETENESS



SOUNDNESS AND COMPLETENESS



SOUNDNESS

If $\Gamma \vdash \varphi$, then $\Gamma \models \varphi$.

If $\Gamma \not\vdash \varphi$, then $\Gamma \not\models \varphi$.

EXAMPLE

All x are $y \not\vdash$ All x are z

To show this, we'll show that

All x are $y \not\models$ All x are z

and then use the **soundness** of the proof system.

And for this last assertion, we can make a model:

$M = \{1, 2, 3\}$, $\llbracket x \rrbracket = \{1\}$, $\llbracket y \rrbracket = \{1, 2\}$, $\llbracket z \rrbracket = \{2, 3\}$.

I have skipped the routine proof that our system is sound:

$$\text{If } \Gamma \vdash \varphi, \text{ then } \Gamma \models \varphi.$$

Perhaps more important is the *converse* of this:

COMPLETENESS

$$\text{If } \Gamma \models \varphi, \text{ then } \Gamma \vdash \varphi.$$

It is important to see what this says.

Completeness tells us that if Γ semantically implies ψ , then we can find one of our (semantics-free!) proof trees showing $\Gamma \vdash \psi$.

DEFINITION

A **preorder** is a pair (P, \leq) ,
where P is a set
and \leq is a relation on it with the following properties:

REFLEXIVE $p \leq p$

TRANSITIVE If $p \leq q$ and $q \leq r$, then $p \leq r$.

CAUTION

We **need not have** the following property:

ANTI-SYMMETRIC if $p \leq q$ and $q \leq p$, then $p = q$.

An anti-symmetric preorder is a **partially ordered set (poset)**.

A SIMPLE EXAMPLE OF A PREORDER

Let N be the **positive and negative numbers**, and let

$n \leq m$ iff n divides m with no remainder

We have facts like

$2 \leq 4$	$2 \leq -4$	$-5 \leq 500$
$3 \not\leq 4$	$4 \leq 4$	$74 \not\leq 4$
$3 \leq 6$	$4 \leq -2900$	$-3 \not\leq -2$

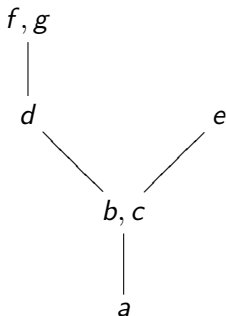
We would in addition have $6 \equiv -6$, because $6 \leq -6$ and $-6 \leq 6$.

Of course 6 and -6 are **not equal**,
so this preorder is not a partial order.

HASSE DIAGRAMS OF PREORDERS

We draw the preorder with \leq indicated by “going up (or equal)” and equivalent elements drawn right next to each other.

In any preorder, $\downarrow p = \{x : x \leq p\}$.



$$\downarrow f = \downarrow g = \{a, \dots, g\} \setminus \{e\}$$

$$\downarrow d = \{a, b, c, d\}, \downarrow e = \{a, b, c, e\}$$

$$\downarrow b = \{a, b, c\} = \downarrow c$$

$$\downarrow a = \{a\}$$

\downarrow is **monotone**: if $p \leq q$, then $\downarrow p \subseteq \downarrow q$.

PROOF OF COMPLETENESS: THE CANONICAL MODEL

Suppose that $\Gamma \models \text{All } x \text{ are } y$.

At this point, we're going to make up a special model called the canonical model.

Let the universe M be the set of nouns (!).

DEFINITION

Define $a \leq_{\Gamma} b$ to mean that $\Gamma \vdash \text{All } a \text{ are } b$.

Check that \leq_{Γ} is reflexive and transitive, using the logic.

So we have a preorder, called the canonical preorder of Γ .

To make a model, we must interpret the nouns.

We get to interpret the nouns any way we like.

We use the downsets in the canonical preorder of Γ :

$$[a] = \downarrow a = \{b : b \leq_{\Gamma} a\}$$

CLAIM: $\mathcal{M} \models \Gamma$.

PROOF OF COMPLETENESS: THE CANONICAL MODEL

HERE IS THE PROOF THAT $\mathcal{M} \models \Gamma$

Suppose Γ contains **All c are d**.

We must check that $\llbracket c \rrbracket \subseteq \llbracket d \rrbracket$ in the model which we defined.

Let $w \in \llbracket c \rrbracket$. So $w \leq_{\Gamma} c$.

Thus $\Gamma \vdash$ All w are c .

But look:

$$\frac{\begin{array}{c} \vdots \\ \text{All } w \text{ are } c \end{array} \quad \text{All } c \text{ are } d}{\text{All } w \text{ are } d} \text{ BARBARA}$$

All the leaves are in Γ , and the tree shows that $\Gamma \vdash$ All w are d .

Thus $w \in \llbracket d \rrbracket$.

Since w is arbitrary, we have shown that $\llbracket c \rrbracket \subseteq \llbracket d \rrbracket$.

The \vdots notation means that we have some proof tree over Γ whose root is All w are c .

We are therefore showing how to extend some such tree with one more step.

PROOF OF COMPLETENESS, CONCLUDED

Where are we?

We assumed that $\Gamma \models \text{All } x \text{ are } y$.

We then made up a model \mathcal{M} .

By the Lemma, our model \mathcal{M} makes all of the sentences in Γ true.

So in this model, $\llbracket x \rrbracket \subseteq \llbracket y \rrbracket$.

(Why is this true? It's a key point!)

But $x \in \llbracket x \rrbracket$, since we can prove *All x are x* from (any) Γ .

(This is where we use the (AXIOM) rule in our system.)

So $x \in \llbracket y \rrbracket$.

(Again, why is this true?)

This **means** that $\Gamma \vdash \text{All } x \text{ are } y$, as desired.

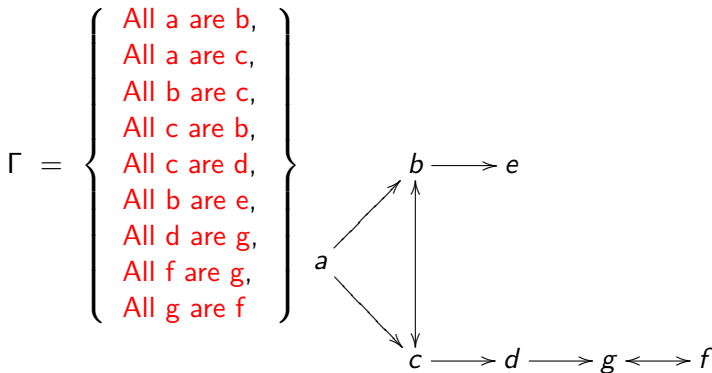


We have proved the completeness of our logical system A .

But we have not done it in a way that is
algorithmically meaningful.

That is, we have not given an algorithm to tell whether or not
 $\Gamma \vdash \varphi$.

Our next order of business is to do this, using **graphs**.



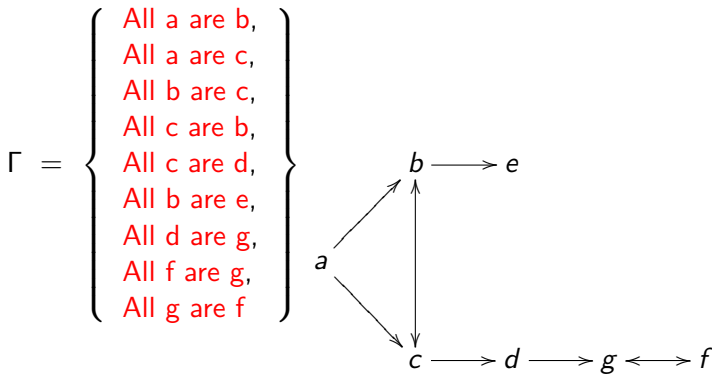
This is called the **All**-graph of Γ .

Let (G, \rightarrow) be any graph.

We get a preorder (G, \rightarrow^*) with the same points by

$g \rightarrow^* h$ iff we can go from g to h
in 0 or more steps, following the arrows

WE HAVE ALREADY SEEN THAT EVERY SET Γ GIVES A GRAPH

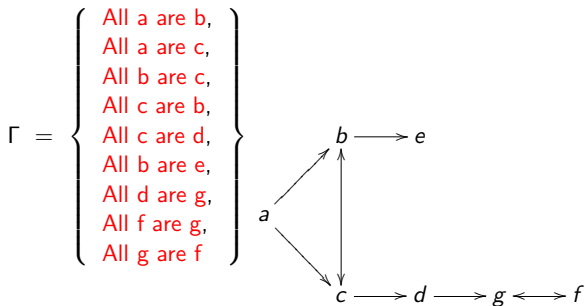


The graph just goes by looking at Γ .

If **All x are y** is in Γ , we put an edge **from x to y** in the graph.

In this case, we would write $x \xrightarrow{\Gamma} y$.

WE HAVE ALREADY SEEN THAT EVERY SET Γ GIVES A GRAPH



We use $\xrightarrow[\Gamma]{*}$ for the preorder relation determined by the graph.

In the preorder, $a \xrightarrow[\Gamma]{*} b$, $b \xrightarrow[\Gamma]{*} c$, $c \xrightarrow[\Gamma]{*} d$, $b \xrightarrow[\Gamma]{*} e$, $a \xrightarrow[\Gamma]{*} e$, $b \xrightarrow[\Gamma]{*} d$,
 $d \xrightarrow[\Gamma]{*} g$, $d \xrightarrow[\Gamma]{*} f$, $g \xrightarrow[\Gamma]{*} f$, $f \xrightarrow[\Gamma]{*} g$, $a \xrightarrow[\Gamma]{*} e$, $a \xrightarrow[\Gamma]{*} c$, $a \xrightarrow[\Gamma]{*} d$, $a \xrightarrow[\Gamma]{*} g$, $a \xrightarrow[\Gamma]{*} f$,
 $b \xrightarrow[\Gamma]{*} c$, $b \xrightarrow[\Gamma]{*} d$, $b \xrightarrow[\Gamma]{*} g$, $b \xrightarrow[\Gamma]{*} f$, $c \xrightarrow[\Gamma]{*} g$, $c \xrightarrow[\Gamma]{*} f$.

Also $x \xrightarrow[\Gamma]{*} x$ for all x .

Fix a set Γ .

Let x and y be any atoms.

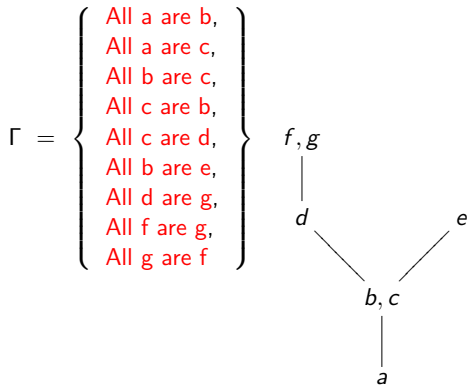
Then the following are equivalent:

- ① $x \leq_{\Gamma} y$.
(That is, $\Gamma \vdash \text{All } x \text{ are } y$.)
- ② $x \xrightarrow{*}_{\Gamma} y$.
(That is, there is a path from x to y in the All-graph of Γ .)

THE POINT

There are algorithms for finding the **reachability relation** in any graph,
in particular, we can build the All-graph of Γ and then find $\xrightarrow{*}_{\Gamma}$.

Γ INDUCES A GRAPH, THE GRAPH INDUCES A PREORDER HERE IS A PICTURE OF THAT PREORDER



The set P here is $\{a, \dots, g\}$.

The order is $\xrightarrow[\Gamma]{*}$, which we just saw listed in full.

We draw the order with $\xrightarrow[\Gamma]{*}$ indicated by going upwards.

Note that $b \equiv c$ and $f \equiv g$.

A CHALLENGE QUESTION FROM BEFORE:
DOES $\Gamma \vdash \text{All } d \text{ are } e$?

All a are b

All a are c

All b are c

All c are b

All c are d

All b are e

All d are g

All f are g

All g are f

$$\llbracket a \rrbracket = \{a\}$$

$$\llbracket b \rrbracket = \{a, b, c\}$$

$$\llbracket c \rrbracket = \{a, b, c\}$$

$$\llbracket d \rrbracket = \{a, b, c, d\}$$

$$\llbracket e \rrbracket = \{a, b, c, e\}$$

$$\begin{aligned}\llbracket f \rrbracket &= \{a, \dots, g\} \setminus \{e\} \\ &= \{a, b, c, d, f, g\}\end{aligned}$$

$$\llbracket g \rrbracket = \{a, \dots, g\} \setminus \{e\}$$

Γ is listed on the left.

We construct the **canonical model** of Γ .

It is shown on the right.

Since $\llbracket d \rrbracket$ is not a subset of $\llbracket e \rrbracket$, $\Gamma \not\models \text{All } d \text{ are } e$.

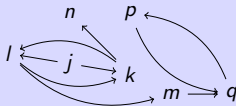
By soundness, $\Gamma \not\vdash \text{All } d \text{ are } e$.

AN EXAMPLE OF EVERYTHING

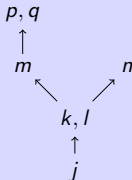
A set Γ

All j are k , All l are m ,
All j are l , All k are n ,
All k are l , All m are q ,
All l are k , All p are q ,
All q are p

the all-graph of Γ



the associated preorder



the canonical model of Γ

$\llbracket j \rrbracket = \{j\}$
 $\llbracket k \rrbracket = \{j, k, l\}$
 $\llbracket l \rrbracket = \{j, k, l\}$
 $\llbracket m \rrbracket = \{j, k, l, m\}$
 $\llbracket n \rrbracket = \{j, k, l, n\}$
 $\llbracket p \rrbracket = \{j, k, l, m, p, q\}$
 $\llbracket q \rrbracket = \{j, k, l, m, p, q\}$

Completeness: For all Γ and φ ,
if $\Gamma \not\vdash \varphi$,
then there is some $\mathcal{M} \models \Gamma$ where φ is false.

Characteristic Model Property:
For all Γ , there is a model $\mathcal{M} \models \Gamma$
such that for all φ ,
if $\Gamma \not\vdash \varphi$, then φ is false in \mathcal{M} .

The main facts are

- ① $\mathcal{M} \models \Gamma$
- ② If $\mathcal{M} \models \text{all } x \text{ are } y$, then $\Gamma \vdash \text{all } x \text{ are } y$.

Completeness: For all Γ and φ ,
 if $\Gamma \not\vdash \varphi$,
 then there is some $\mathcal{M} \models \Gamma$ where φ is false.

Characteristic Model Property:

For all Γ , there is a model $\mathcal{M} \models \Gamma$
 such that for all φ ,
 if $\Gamma \not\vdash \varphi$, then φ is false in \mathcal{M} .

This model is the **canonical model of Γ** .

The universe of the model is the set of nouns (=variables) that occur in Γ .

The definition of the model is

$$[[a]] = \downarrow a = \{b : b \leq_{\Gamma} a\} = \{b : \Gamma \vdash \text{All } b \text{ are } a\}$$

The main facts are

- ① $\mathcal{M} \models \Gamma$
- ② If $\mathcal{M} \models \text{all } x \text{ are } y$, then $\Gamma \vdash \text{all } x \text{ are } y$.

HOMEWORK: CHANGE THE SEMANTICS

Let's take a new word All^* , and make a logical language using the sentences $All^* x y$ for all nouns x and y .

SEMANTICS

$$\mathcal{M} \models All^* x y \quad \text{iff} \quad \llbracket x \rrbracket \neq \emptyset \text{ and } \llbracket x \rrbracket \subseteq \llbracket y \rrbracket$$

Notice that if we have a model \mathcal{M} and a noun x where $\llbracket x \rrbracket = \emptyset$, then automatically $\mathcal{M} \not\models All^* x y$, no matter what y is.

LOGIC (NO AXIOM)

$$\frac{All^* x y}{All^* x x} \text{ R} \qquad \frac{All^* x y}{All^* y y} \text{ S} \qquad \frac{All^* x y \quad All^* y z}{All^* x z} \text{ B}$$

HOMEWORK: CHANGE THE SEMANTICS

Let's take a new word All^* , and make a logical language using the sentences $All^* x y$ for all nouns x and y .

SEMANTICS

$$\mathcal{M} \models All^* x y \quad \text{iff} \quad \llbracket x \rrbracket \neq \emptyset \text{ and } \llbracket x \rrbracket \subseteq \llbracket y \rrbracket$$

Notice that if we have a model \mathcal{M} and a noun x where $\llbracket x \rrbracket = \emptyset$, then automatically $\mathcal{M} \not\models All^* x y$, no matter what y is.

LOGIC (NO AXIOM)

$$\frac{All^* x y}{All^* x x} \text{ R} \qquad \frac{All^* x y}{All^* y y} \text{ S} \qquad \frac{All^* x y \quad All^* y z}{All^* x z} \text{ B}$$

HOMEWORK

Prove the completeness of this system.