

EXTENSIONS TO THE LOGIC OF *All x are y*:
VERBS, RELATIVE CLAUSES, AND *Only*

Larry Moss

Indiana University

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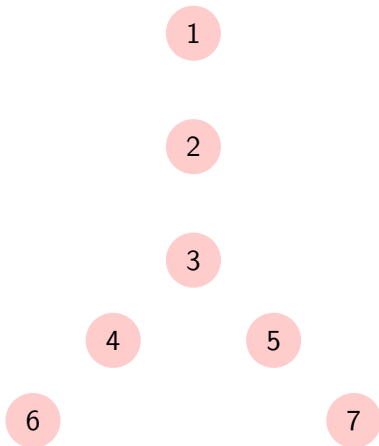
AN EXAMPLE THAT WE'LL SEE A FEW TIMES

Consider the model \mathcal{M} with universe $\{1, \dots, 7\}$, and with interpretations of three unary atoms: hawks, birds, and turtles,

$$\llbracket \text{hawks} \rrbracket = \{1\}$$

$$\llbracket \text{birds} \rrbracket = \{1, 6\}$$

$$\llbracket \text{turtles} \rrbracket = \{3, 5, 7\}$$



We want to use **see** as a (generic) **transitive verb**,
that is, a verb which takes a direct object.

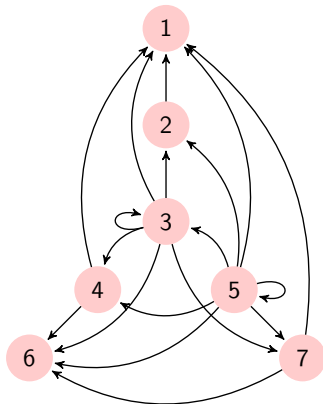
The interpretation $\llbracket \text{see} \rrbracket$ should not be a subset of the model.
It should be a **set of ordered pairs**.

HERE'S ONE WAY TO DO IT

[[hawks]] = {1}

[[birds]] = {1, 6}

[[turtles]] = {3, 5, 7}



[[see]] = {(2, 1), (3, 1), (3, 2), (3, 4), (3, 6), (3, 7), (4, 1), (4, 6),
(5, 1), (5, 2), (5, 3), (5, 4), (5, 5), (5, 6), (5, 7), (7, 1), (7, 6)}

The **formal** specification of the semantics is the one just above.
But the picture is clearer, and so we prefer to use it whenever we
can.

Compared to the language \mathcal{A} from before, we now have a **bigger basic syntax**, since we have transitive verbs.

We will have more than one transitive verb, just as we already have more than one noun.

(We still have to say what the sentences are going to be.)

And we are going to interpret the transitive verbs by sets of ordered pairs in a model.

When we want to draw a model, the interpretation of a transitive verb will be drawn with arrows, as we do with graphs.

OUR FIRST LANGUAGE IN THIS LECTURE, $\mathcal{A}(\mathcal{RC})$

We start with two sets:

- ▶ a set \mathbf{P} of **unary atoms**, also called **nouns**.
- ▶ a set \mathbf{R} of **binary atoms**, also called **verbs**.

We make **terms** as follows:

- ▶ If x is a unary atom, then x is a term.
- ▶ If x is a binary atom and x is a term, then **r all x** is a term.

We make **sentences** as follows:

- ▶ If x and y are terms, then

All x y

is a sentence.

These are the only sentences in the language.

We frequently use parentheses to make things more readable.

EXAMPLES OF THE SYNTAX OF $\mathcal{A}(\mathcal{RC})$

Let's say

- ▶ $\mathbf{P} = \{\text{dogs, cats, birds, ants, } \dots\}$
- ▶ $\mathbf{R} = \{\text{see, like, hate, fear, respect, } \dots\}$

Here are some **terms** of $\mathcal{A}(\mathcal{RC})$:

- ▶ dogs
- ▶ see all dogs
- ▶ respect all (see all dogs)
- ▶ love all (respect all (see all dogs))

Note that there are infinitely many terms, and terms may occur in terms.

EXAMPLES OF THE SYNTAX OF $\mathcal{A}(\mathcal{RC})$

Let's say

- ▶ $\mathbf{P} = \{\text{dogs, cats, birds, ants, ...}\}$
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Here are some **terms** of $\mathcal{A}(\mathcal{RC})$:

- ▶ dogs
- ▶ see all dogs
- ▶ respect all (see all dogs)
read as **respect all who see all dogs**
- ▶ love all (respect all (see all dogs))
read as **love all who respect all who see all dogs**

Note that there are infinitely many terms, and terms may occur in terms.

We read these in English using relative clauses.

GRAMMAR LESSON: RELATIVE CLAUSES

Every senator who likes the president sang.

Every senator who the president likes sang.

The relative clauses are in red just above.

The first is a subject relative clause,
the second is an object relative clause

GRAMMAR LESSON: RELATIVE CLAUSES

Every senator who likes the president sang.

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The first is a subject relative clause,

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Like adjectives, relative clauses modify a head noun:

Every female senator sang.

In English, adjectives come before their head noun,
and relative clauses come after it.

GRAMMAR LESSON: RELATIVE CLAUSES

Every senator who likes the president sang.

Every senator who the president likes sang.

The relative clauses are in red just above.

The first is a subject relative clause,
the second is an object relative clause

In this lecture, all the relative clauses will be
subject relative clauses.

And there will be no head nouns.

(Both restrictions can be lifted with more work.)

EXAMPLES OF THE SYNTAX OF $\mathcal{A}(\mathcal{RC})$

Here are some **sentences** of $\mathcal{A}(\mathcal{RC})$:

- ▶ all dogs animals
- ▶ all dogs cats
- ▶ all dogs (see all cats)
- ▶ all (see all cats) (fear all tigers)
We read this one as “all **who** see all cats fear all tigers”.
- ▶ all (love all dogs) (hate all (love all cats))
We read this one as
“all **who** love all dogs (**also**) hate (all **who** love all cats)”.

COMMENT

The important point here is that our syntax deviates from the standard syntax in linguistics and of course from the standard syntax in logic.

PROOFS BY INDUCTION ON TERMS

Because the terms of the language is defined by **recursion**,
one needs **induction** to prove a sentence like

for all terms t , _____

INDUCTION ON TERMS

- ▶ Prove _____ for the unary atoms.
- ▶ Fix a term t .
Assume _____ for t ,
and then prove that for all binary atoms (=verbs) r ,
_____ holds for the term r all t .

If you can do these two things,
you can conclude _____ for all terms.

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EDUCATIONAL POINT

I'm not going to do any proof by induction in this lecture,
since you all are advanced students.

But in a low-level course, this subject could be used to **teach**
induction.

A model \mathcal{M} for $\mathcal{A}(\mathcal{RC})$ is

$$\mathcal{M} = (M, \llbracket \cdot \rrbracket).$$

where M is a set, called (as before) the **universe**, together with **interpretations** of the atoms.

For each unary atom p , we have an interpretation $\llbracket p \rrbracket \subseteq M$.
And for each binary atom r , we have an interpretation $\llbracket r \rrbracket \subseteq M \times M$.

SEMANTICS: INTERPRETATIONS OF COMPLEX TERMS

We use an inductive definition to interpret the terms.

The model comes with interpretations of the unary atoms, the “base case” of terms.

And the general case is

$$\llbracket r \text{ all } x \rrbracket = \{m \in M : \text{for all } n \in \llbracket x \rrbracket, (m, n) \in \llbracket r \rrbracket\}.$$

And then we say

$$\mathcal{M} \models \text{All } x \ y \quad \text{iff} \quad \llbracket x \rrbracket \subseteq \llbracket y \rrbracket$$

Here x and y are any terms.

If $\llbracket x \rrbracket = \emptyset$ in a given model, then according to our definition

$$\begin{aligned} \llbracket r \text{ all } x \rrbracket &= \{m \in M : \text{for all } n \in \llbracket x \rrbracket, (m, n) \in \llbracket r \rrbracket\} \\ &= \{m \in M : \text{for all } n \in \emptyset, (m, n) \in \llbracket r \rrbracket\} \\ &= M \end{aligned}$$

This means that if $\llbracket x \rrbracket = \emptyset$ in a given model \mathcal{M} , then every sentence like

all birds (like all x)

comes out **true** in this model \mathcal{M} .

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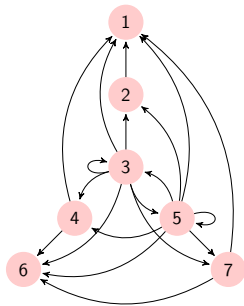
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$\llbracket \text{hawks} \rrbracket = \{1\}$

$\llbracket \text{birds} \rrbracket = \{1, 6\}$

$\llbracket \text{turtles} \rrbracket = \{3, 5, 7\}$

$\llbracket \text{see} \rrbracket$ as shown



In this model,

$\llbracket \text{see all hawks} \rrbracket = \{2, 3, 4, 5, 7\}$

$\llbracket \text{see all birds} \rrbracket = \{3, 4, 5, 7\}$

$\llbracket \text{see all turtles} \rrbracket = \{3, 5\}$

$\llbracket \text{see all (see all hawks)} \rrbracket = \{3, 5\}$

Here are some examples of sentences false and true in the model:

$\mathcal{M} \not\models \text{All (see all hawks) (see all birds)}$

$\mathcal{M} \models \text{All (see all turtles) (see all (see all hawks))}$

$\mathcal{M} \models \text{All (see all (see all hawks)) (see all turtles)}$

THE USUAL DEFINITIONS OF SEMANTIC CONSEQUENCE

We say that $\mathcal{M} \models \Gamma$ iff $\mathcal{M} \models \varphi$ for every $\varphi \in \Gamma$.

We say that $\Gamma \models \varphi$ iff for all \mathcal{M} : if $\mathcal{M} \models \Gamma$, then also $\mathcal{M} \models \varphi$.

We read this as

- Γ logically implies φ
- or Γ semantically implies φ
- or φ is a semantic consequence of Γ .

By now in a course, the lines above should be automatic.

EXAMPLES OF THE SEMANTIC CONSEQUENCE RELATION \models

All skunks mammals \models All (love all mammals) (love all skunks)

All skunks mammals $\not\models$ All (love all skunks) (love all mammals)

All skunks mammals
 \models All (hate all (love all skunks)) (hate all (love all mammals))

MORE EXAMPLES OF THE SEMANTIC CONSEQUENCE RELATION \models

All skunks mammals, All dogs chase all mammals \models All dogs chase all skunks

More generally, for all unary atoms x , y , and z , and all binary atoms r ,

$$\text{All } x \ y, \text{All } z \ r \ \text{all } y \models \text{All } z \ r \ \text{all } x$$

THE LOGIC $\mathcal{A}(\mathcal{RC})$

$$\frac{}{\text{All } x \ x} \text{ AXIOM} \quad \frac{\text{All } x \ y \quad \text{All } y \ z}{\text{All } x \ z} \text{ BARBARA}$$

$$\frac{\text{All } x \ (r \ \text{all } y) \quad \text{All } z \ y}{\text{All } x \ (r \ \text{all } z)} \text{ DOWN}$$

THE LOGIC $\mathcal{A}(\mathcal{RC})'$

$$\frac{}{\text{All } x \ x} \text{ AXIOM} \quad \frac{\text{All } x \ y \quad \text{All } y \ z}{\text{All } x \ z} \text{ BARBARA}$$

$$\frac{\text{All } y \ x}{\text{All } (r \ \text{all } x) \ (r \ \text{all } y)} \text{ ANTI}$$

Note that we are using this with x , y , and z as variables ranging over terms,
not as variables ranging over unary atoms the way we did with \mathcal{A} .

We use a different font for the names of the **logical systems** than for the name of the **logical language**, $\mathcal{A}(\mathcal{RC})$.

TWO EXAMPLES OF DERIVATIONS IN A(RC)':

First, a derivation showing that every instance of (DOWN) is provable in A(RC)':

$$\frac{\text{All } x \text{ (see all } y) \quad \frac{\text{All } z \text{ } y}{\text{All (see all } y)(\text{see all } z)} \text{ ANTI}}{\text{All } x \text{ (see all } z)} \text{ BARBARA}$$

Second, a proof tree corresponding to an example from earlier in this lecture:

$$\frac{\frac{\text{All skunks mammals}}{\text{All (love all mammals) (love all skunks)} \text{ ANTI}}{\text{All (hate all (love all skunks)) (hate all (love all mammals))} \text{ ANTI}} \text{ ANTI}$$

WE ALSO CAN PROVE
EVERY INSTANCE OF (ANTI) IN A(RC):

THE LOGIC A(RC)

$$\frac{}{\text{All } x \ x} \text{ AXIOM} \qquad \frac{\text{All } x \ y \quad \text{All } y \ z}{\text{All } x \ z} \text{ BARBARA}$$

$$\frac{\text{All } x \ (r \ \text{all } y) \quad \text{All } z \ y}{\text{All } x \ (r \ \text{all } z)} \text{ DOWN}$$

$$\frac{\frac{}{\text{All } (r \ \text{all } x) \ (r \ \text{all } x)} \text{ AXIOM} \quad \text{All } y \ x}{\text{All } (r \ \text{all } x) \ (r \ \text{all } y)} \text{ DOWN}$$

In (DOWN), we took x to be $(r \ \text{all } x)$,
 y to be x ,
 z to be y .

THE TWO LOGICS PROVE EACH OTHER'S RULES

THE LOGIC A(RC)

$$\frac{}{\text{All } x \ x} \text{ AXIOM} \quad \frac{\text{All } x \ y \quad \text{All } y \ z}{\text{All } x \ z} \text{ BARBARA}$$

$$\frac{\text{All } x \ (r \ \text{all } y) \quad \text{All } z \ y}{\text{All } x \ (r \ \text{all } z)} \text{ DOWN}$$

THE LOGIC A(RC)'

$$\frac{}{\text{All } x \ x} \text{ AXIOM} \quad \frac{\text{All } x \ y \quad \text{All } y \ z}{\text{All } x \ z} \text{ BARBARA}$$

$$\frac{\text{All } y \ x}{\text{All } (r \ \text{all } x) \ (r \ \text{all } y)} \text{ ANTI}$$

In the first logic, we can prove all instances of the rules of the second logic.

In the second logic, we can prove all instances of the rules of the first logic.

In a few minutes, we'll use this to show the following result:

THEOREM

If $\Gamma \vdash \varphi$ in A(RC), then $\Gamma \vdash \varphi$ in A(RC)'.

If $\Gamma \vdash \varphi$ in A(RC)', then $\Gamma \vdash \varphi$ in A(RC).

THE FIRST HARD DERIVATION IN THIS COURSE

Let us assume the following:

All who hate all ducks are cats

All who love all pigs see all cats

All who see all who hate all ducks are cats

and then prove that

All who love all pigs are cats.

You should try this yourself for a few minutes.

THE FIRST HARD DERIVATION IN THIS COURSE

Let us assume the following:

All who hate all ducks are cats

All who love all pigs see all cats

All who see all who hate all ducks are cats

and then prove that

All who love all pigs are cats.

Here is a derivation in A(RC):

$$\frac{\frac{\text{All (hate all d) c} \quad \text{All (love all p) (see all c)}}{\text{All (love all p) (see all (hate all d))}} \text{DOWN} \quad \text{All (see all (hate all d)) c}}{\text{All (love all p) c}} \text{BARBARA}$$

As you can see from trying it yourself, finding a derivation is difficult.

One problem is that when we build trees from the bottom up in a system with (BARBARA), we don't know what the "middle term" should be: it could be anything!

THEOREM

Let Γ be any set of sentences in the logic $\mathcal{A}(\mathcal{RC})$.

Suppose that \mathcal{T} is a proof tree over Γ , and let the root of \mathcal{T} be All x are y .

Then in all models \mathcal{M} , $\llbracket x \rrbracket \subseteq \llbracket y \rrbracket$.

We have

- ▶ a syntax of terms and sentences
- ▶ a semantics
- ▶ two proof systems, and the proof that they are basically the same
- ▶ soundness of the logics

Still to come

- ▶ completeness of our system
- ▶ algorithmic work to tell whether or not a given set Γ implies a given sentence φ .

THE CANONICAL MODEL OF A SET Γ OF SENTENCES IN $\mathcal{A}(\mathcal{RC})$

Suppose that we are given a set Γ in this language $\mathcal{A}(\mathcal{RC})$.

We aim to build a **canonical model** $\mathcal{M} = \mathcal{M}_\Gamma$
with two properties:

- ▶ $\mathcal{M} \models \Gamma$
- ▶ For all φ , if $\mathcal{M} \models \varphi$, then $\Gamma \vdash \varphi$.

WHY DO WE DO THIS?

This would prove the completeness theorem for our logic $\mathcal{A}(\mathcal{RC})$.
Please be sure that you can do this step yourself.

THE CANONICAL MODEL OF A SET Γ OF SENTENCES IN $\mathcal{A}(\mathcal{RC})$

Here is the definition.

In it, p is a unary atom (noun) and r a binary atom (verb).

And then we define

$$\begin{aligned} M &= \text{all terms built from our unary and binary atoms} \\ \llbracket p \rrbracket &= \{x : \Gamma \vdash \text{All } x \ p\} \\ \llbracket r \rrbracket &= \{(x, y) : \Gamma \vdash \text{All } x \ (r \text{ all } y)\} \end{aligned}$$

The interpretation of unary atoms is just like we saw it in the canonical model construction for \mathcal{A} .

But the interpretation of binary atoms is new, and it is more subtle.

BEFORE WE DO ANY OF THE THEORY, LET'S DO A SIMPLE EXAMPLE

Let **P** have just two atoms: p and q .

Let **R** have just one binary atom: see.

Let's draw the picture of the canonical model of

$$\Gamma = \{\text{All } p \text{ } q\}$$

There are infinitely many terms:

p

see all p

see all (see all p)

see all (see all (see all p))

\vdots

q

see all q

see all (see all q)

see all (see all (see all q))

\vdots

BEFORE WE DO ANY OF THE THEORY, LET'S DO A SIMPLE EXAMPLE

Let **P** have just two atoms: p and q .

Let **R** have just one binary atom: see.

Let's draw the picture of the canonical model of

$$\Gamma = \{\text{All } p \text{ } q\}$$

There are infinitely many terms, and **we abbreviate them:**

p_0 p

p_1 see all p

p_2 see all (see all p)

p_3 see all (see all (see all p))

\vdots

q_0 q

q_1 see all q

q_2 see all (see all q)

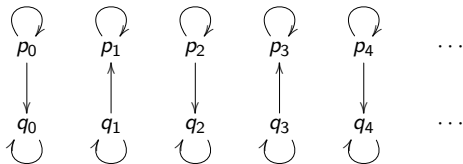
q_3 see all (see all (see all q))

\vdots

THE PICTURE OF THE “ARE” RELATION

$$\{(x, y) : \Gamma \vdash \text{ALL } x \ y\}$$

REMEMBER THAT Γ HERE IS $\{\text{All } p \ q\}$.



An arrow $x \rightarrow y$ above means that $\Gamma \vdash \text{all } x \ y$.

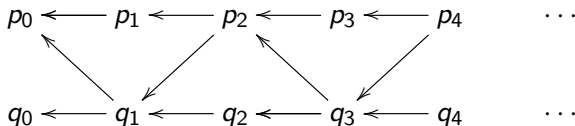
These arrow tell us that in the canonical model

$$\begin{aligned} \llbracket p \rrbracket &= \{p_0\} \\ \llbracket q \rrbracket &= \{p_0, q_0\} \end{aligned}$$

But the picture on this slide is not the interpretation of the verb see.

PICTURE OF $\llbracket \text{see} \rrbracket$ IN THE CANONICAL MODEL OF Γ

REMEMBER THAT Γ HERE IS $\{\text{All } p \ q\}$.

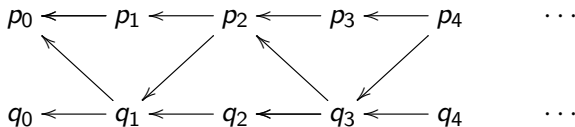


An arrow $x \rightarrow y$ in the picture above means that $\Gamma \vdash \text{all } x$ (see all y).

The arrow $x \rightarrow y$ above does not mean that $\Gamma \vdash \text{all } x \ y$.

PICTURE OF $\llbracket \text{see} \rrbracket$ IN THE CANONICAL MODEL OF Γ

REMEMBER THAT Γ HERE IS $\{\text{All } p \ q\}$.



Here is the idea:

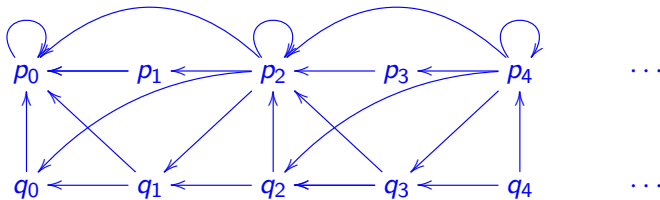
Think of the node x as a “random” x .

If we can prove from Γ that **All x see all y** ,
then we want to put a $\llbracket \text{see} \rrbracket$ -arrow from x to y .

Here is another set

$$\Gamma = \{ \text{All } p \text{ are } q, \text{All } q \text{ (see all } p) \} .$$

Its canonical model is



$$[[p]] = \{p_0\}$$

$$[[q]] = \{p_0, q_0\}$$

LEMMA (TRUTH LEMMA)

Let Γ be a set of sentences in $\mathcal{A}(\mathcal{RC})$,
and let \mathcal{M} be the canonical model of Γ .
For all terms t ,

$$\llbracket t \rrbracket = \{y : \Gamma \vdash \text{All } y \ t\}$$

PROOF.

By induction on terms (what else?). □

SECOND LEMMA

THIS IS BASICALLY WHAT WE SAW FOR \mathcal{A}

LEMMA

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

PROOF.

Take a sentence in Γ , say $\text{All } u \ v$.

To see that this sentence holds in \mathcal{M} , let $y \in \llbracket u \rrbracket$.

By the Truth Lemma, $\Gamma \vdash \text{All } y \ u$.

And then using (BARBARA), we have $\Gamma \vdash \text{All } y \ v$.

Therefore, $y \in \llbracket v \rrbracket$.

So we have shown that $\llbracket u \rrbracket \subseteq \llbracket v \rrbracket$, just as desired. □

THIRD LEMMA

THIS, TOO, IS BASICALLY WHAT WE SAW FOR \mathcal{A}

LEMMA

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

PROOF.

Let φ be $\text{All } a \ b$.

Let \mathcal{M} be the canonical model.

Suppose that $\llbracket a \rrbracket \subseteq \llbracket b \rrbracket$ in \mathcal{M} .

By (AXIOM), $\Gamma \vdash \text{All } a \ a$.

So by the Truth Lemma, $a \in \llbracket a \rrbracket$.

And so $a \in \llbracket b \rrbracket$.

By the Truth Lemma again, we have $\Gamma \vdash \text{All } a \ b$. □

THEOREM

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

PROOF.

Let \mathcal{M} be the canonical model of Γ .

By the second lemma, $\mathcal{M} \models \Gamma$.

Thus $\mathcal{M} \models \varphi$.

And so by the third lemma, $\Gamma \vdash \varphi$.



We have

- ▶ a syntax of terms and sentences
- ▶ a semantics
- ▶ a proof system
- ▶ a hint about soundness
- ▶ **we just did** the completeness of our system

Still to come

- ▶ algorithmic work to tell whether or not a given set Γ implies a given sentence φ .

Here is a question: does the conclusion follow?

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All (see all hawks) (see all birds)



Here is a question: does the conclusion follow?

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All (see all hawks) (see all birds)



This is too hard to do by guessing,
and anyways we need a systematic approach.

We can't examine all the models in the world:
there are too many.

The canonical model is infinite.

What to do???????

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

??? All (see all hawks) (see all birds)

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

??? All (see all hawks) (see all birds)

Suppose (questionably) that **if there were** a proof, there would be one that only uses the terms above:

hawks	see all hawks	see all (see all hawks)
birds	see all birds	
turtles	see all turtles	

Then our life would be **much easier**, because we can simply generate all the consequences of our rules on this set of seven terms.

All hawks birds
 All (see all turtles) (see all (see all hawks))
 All (see all (see all hawks)) turtles
 All turtles (see all birds)
 ??? All (see all hawks) (see all birds)

The problem is that there **might** be a proof that used some humongous term $t_{\text{humongous}}$

$$\frac{\begin{array}{c} \vdots \\ \text{All (see all hawks)} \end{array} t_{\text{humongous}} \quad \text{All } t_{\text{humongous}} \begin{array}{c} \vdots \\ \text{(see all birds)} \end{array}}{\text{All (see all hawks) (see all birds)}} \quad b$$

Our idea might miss that proof.

We'll see the general algorithm **after we do an example of it.**

Let's take M to be the terms listed below:

hawks	see all turtles
see all hawks	birds
see all (see all hawks)	turtles
see all birds	

These are just the terms that occur in Γ and φ .

LET'S TRY THIS TOGETHER

Start with

$$\Gamma \cup \{\text{All } x \ x : x \in M\}$$

Generate all the sentences which we can prove from the set above by using (BARBARA) and (DOWN).

We call this set Γ^* .

The main point is that we only generate **finitely many sentences** in this way (note that we are using (DOWN) and not (ANTI)), and we can do all of this work algorithmically.

HERE'S WHAT I GET

WE'RE ASKING WHETHER $\Gamma \vdash$ All (see all hawks) (see all birds) OR NOT

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All x x for $x \in M$

All (see all birds) (see all hawks)

All (see all turtles) (see all (see all (see all hawks)))

All (see all turtles) turtles

All turtles (see all hawks)

All (see all (see all hawks)) (see all birds)

All (see all (see all hawks)) (see all (see all birds))

All (see all (see all hawks)) (see all turtles)

All (see all turtles) (see all (see all turtles))

All (see all (see all hawks)) (see all hawks)

All (see all turtles) (see all birds)

All (see all turtles) (see all (see all birds))

All (see all turtles) (see all hawks)

All (see all (see all hawks)) (see all (see all (see all hawks)))

HERE'S WHAT I GET

WE'RE ASKING WHETHER $\Gamma \vdash$ All (see all hawks) (see all birds) OR NOT

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All x x for $x \in M$

All (see all birds) (see all hawks)

All (see all turtles) (see all (see all (see all hawks)))

All (see all turtles) turtles

All turtles (see all hawks)

All (see all (see all hawks)) (see all birds)

All (see all (see all hawks)) (see all (see all birds))

All (see all (see all hawks)) (see all turtles)

All (see all turtles) (see all (see all turtles))

All (see all (see all hawks)) (see all hawks)

All (see all turtles) (see all birds)

All (see all turtles) (see all (see all birds))

All (see all turtles) (see all hawks)

All (see all (see all hawks)) (see all (see all (see all hawks)))

The set of sentences above is called Γ^* .

If Γ^* contained the sentence that we asked about at the start, we'd be done.

It doesn't.

And so we'll now show how to make a counter-model from Γ^* .

HERE'S WHAT I GET

WE'RE ASKING WHETHER $\Gamma \vdash$ All (see all hawks) (see all birds) OR NOT

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All x x for $x \in M$

All (see all birds) (see all hawks)

All (see all turtles) (see all (see all (see all hawks)))

All (see all turtles) turtles

All turtles (see all hawks)

All (see all (see all hawks)) (see all birds)

All (see all (see all hawks)) (see all (see all birds))

All (see all (see all hawks)) (see all turtles)

All (see all turtles) (see all (see all turtles))

All (see all (see all hawks)) (see all hawks)

All (see all turtles) (see all birds)

All (see all turtles) (see all (see all birds))

All (see all turtles) (see all hawks)

All (see all (see all hawks)) (see all (see all (see all hawks)))

Now we make a **finite version of the canonical model** from Γ^* .

The universe is M .

$\llbracket u \rrbracket = \{v : \Gamma^* \text{ contains All } v \ u\}$.

$\llbracket r \rrbracket = \{(u, v) : \Gamma^* \text{ contains All } u \ (r \text{ all } v)\}$.

HERE'S WHAT I GET

WE'RE ASKING WHETHER $\Gamma \vdash$ All (see all hawks) (see all birds) OR NOT

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

All x x for $x \in M$

All (see all birds) (see all hawks)

All (see all turtles) (see all (see all (see all hawks)))

All (see all turtles) turtles

All turtles (see all hawks)

All (see all (see all hawks)) (see all birds)

All (see all (see all hawks)) (see all (see all birds))

All (see all (see all hawks)) (see all turtles)

All (see all turtles) (see all (see all turtles))

All (see all (see all hawks)) (see all hawks)

All (see all turtles) (see all birds)

All (see all turtles) (see all (see all birds))

All (see all turtles) (see all hawks)

All (see all (see all hawks)) (see all (see all (see all hawks)))

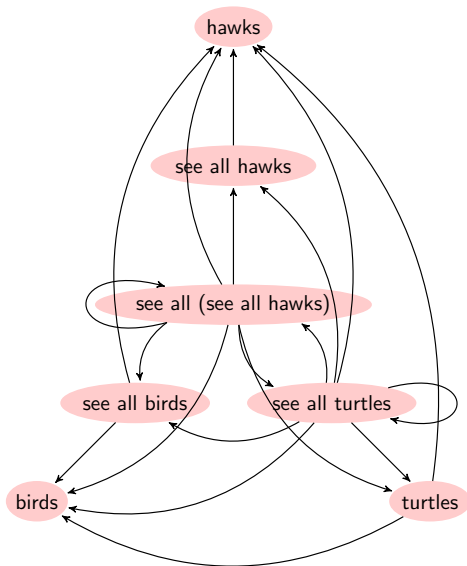
To begin,

[[hawks]] = {hawks}

[[birds]] = {birds, hawks}

[[turtles]] = {turtles, see all turtles, see all (see all hawks)}

THE INTERPRETATION OF **see** IN THIS MODEL



USING NUMBERS INSTEAD OF TERMS

hawks	1
see all hawks	2
see all (see all hawks)	3
see all birds	4
see all turtles	5
birds	6
turtles	7

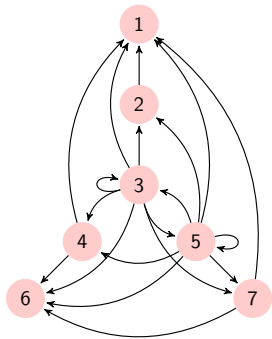
USING NUMBERS INSTEAD OF TERMS

hawks	1
see all hawks	2
see all (see all hawks)	3
see all birds	4
see all turtles	5
birds	6
turtles	7

[[hawks]] = {1}

[[birds]] = {1, 6}

[[turtles]] = {3, 5, 7}



The models are **isomorphic**, and most people would prefer to see the numbers at the end.

WHY WE DID ALL OF THIS

Here is a question: does the conclusion follow?

All hawks birds

All (see all turtles) (see all (see all hawks))

All (see all (see all hawks)) turtles

All turtles (see all birds)

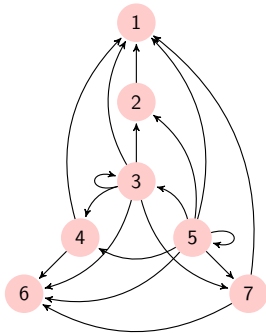
All (see all hawks) (see all birds)

Now we can answer “No” definitively.

[[hawks]] = {1}

[[birds]] = {1, 6}

[[turtles]] = {3, 5, 7}



ALGORITHM TO TELL WHETHER OR NOT $\Gamma \vdash \varphi$

IF $\Gamma \vdash \varphi$, THE ALGORITHM OUTPUTS “YES”.

IF $\Gamma \not\vdash \varphi$, IT OUTPUTS “NO” AND A MODEL OF Γ WHERE φ FAILS.

- 1: $M \leftarrow$ the set of principal terms in $\Gamma \cup \{\varphi\}$, plus the subterms of these terms
- 2: $AX_M \leftarrow \{\text{All } x \ x : x \in M\}$
- 3: $\Gamma^* \leftarrow$ the smallest set with $\Gamma \subseteq \Gamma^*$ and $AX_M \subseteq \Gamma^*$, and closed under the logic A(RC).
If Γ^* contains All $x \ y$ and also All $y \ z$, then Γ^* contains All $x \ z$.
If Γ^* contains All $x \ y$ and All $z \ (r \text{ all } y)$, then Γ^* contains All $z \ (r \text{ all } x)$.
- 4: **if** $\varphi \in \Gamma^*$ **then**
- 5: output “Yes” $\triangleright \Gamma \vdash \varphi$
- 6: **else** \triangleright we construct a counter-model with universe M
- 7: **for all** $u \in \mathbf{P}, r \in \mathbf{R}$ **do**
- 8: $\llbracket u \rrbracket = \{v \in M : \Gamma^* \text{ contains All } v \ u\}$.
- 9: $\llbracket r \rrbracket = \{(u, v) \in M \times M : \Gamma^* \text{ contains All } u \ (r \text{ all } v)\}$.
- 10: **end for**
- 11: output “No” and the model $\mathcal{M} = (M, \llbracket \rrbracket)$ described in lines 7–10.
- 12: **end if**

I'M GOING TO SKIP THE PROOF THAT THE ALGORITHM WORKS

EDUCATIONAL POINT

Small examples could be given as homework or on an exam.

This contrasts with its cousin, **filtration** in modal logic:
It is unfortunately not possible to ask students
to come up with actual examples of filtration.

THE VIEW FROM MODAL LOGIC

AN EARLY REFERENCE FOR \boxplus IS GARGOV, PASSY, AND TINCHEV (1987).

I assume for the moment that you know
the relational (Kripke) semantics of modal logic

A **model** is a set W of “worlds”,
a relation that we are going to write as $\llbracket \text{see} \rrbracket$
(think of it as the “seeing” relation in a model),
and some way to interpret atomic propositions.

The syntax of modal logic has a “box operator” \Box , and we shall
see its semantics below.

But there is a second, less-studied operator, \boxplus , ‘window’.

Let us now compare the main clause in the semantics of both operators.

We associate with the verb **see** two operators, \Box_{see} and \Box_{see} . Their semantics are

$w \models \Box_{\text{see}} \varphi$ iff $w \llbracket \text{see} \rrbracket v$ implies $v \models \varphi$
 “ w sees only φ worlds”

$w \models \Box_{\text{see}} \varphi$ iff $v \models \varphi$ implies $w \llbracket \text{see} \rrbracket v$
 “ w sees all φ worlds”

MORE ON THE MODAL LOGIC CONNECTION

We also add the **universal modality** U , with semantics

$$w \models U\varphi \quad \text{iff} \quad v \models \varphi \text{ for all } v$$

We **translate** $\mathcal{A}(\mathcal{RC})$ into propositional logic + \Box + U ; e.g.,

$$\text{all skunks mammals} \models \text{all (see all mammals) (see all skunks)}$$

translates to

$$U(\text{skunks} \rightarrow \text{mammals}) \models U(\Box_{\text{see}} \text{mammals} \rightarrow \Box_{\text{see}} \text{skunks})$$

and for that matter, we also have

$$U(\text{skunks} \rightarrow \text{mammals}) \models U(\Box_{\text{hate}} \Box_{\text{see}} \text{skunks} \rightarrow \Box_{\text{hate}} \Box_{\text{see}} \text{mammals})$$

$\mathcal{O}(\mathcal{RC})$: ANOTHER ADDITION TO \mathcal{A}

$\mathcal{O}(\mathcal{RC})$ is the logical system defined the same way as $\mathcal{A}(\mathcal{RC})$ was, except that we include terms of the form

r only x

rather than r all x .

Terms may have terms inside (recursion).

Sentences of $\mathcal{O}(\mathcal{RC})$ are the expressions

all x y ,

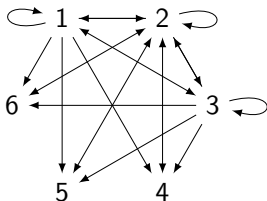
where x and y are terms.

Models are the same.

$$\llbracket r \text{ only } x \rrbracket = \{m \in M : \text{for all } n \text{ if } m \llbracket r \rrbracket n, \text{ then } n \in \llbracket x \rrbracket\}.$$

EXAMPLE OF THE SEMANTICS

Consider the model shown below.



$$\llbracket p \rrbracket = \{2\}$$

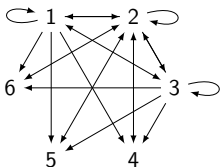
$$\llbracket q \rrbracket = \{1, 2\}$$

We have one verb, see.

- 1 Find $\llbracket \text{see only } p \rrbracket$.
- 2 Find $\llbracket \text{see only } q \rrbracket$.
- 3 Is the sentence All p q true in the model?
- 4 Is the sentence All q (see only q) true in the model?
- 5 Is the sentence All (see only p) (see only q) true in the model?
- 6 Is the sentence All (see only q) (see only p) true in the model?

EXAMPLE OF THE SEMANTICS

Consider the model shown below.



$$\llbracket p \rrbracket = \{2\}$$

$$\llbracket q \rrbracket = \{1, 2\}$$

We have one verb, see.

- 1 Find $\llbracket \text{see only } p \rrbracket$. Answer: $\{4, 6\}$.
- 2 Find $\llbracket \text{see only } q \rrbracket$. Answer: $\{4, 5, 6\}$.
- 3 Is All p q true in the model?
Answer: Yes, because $\{2\} \subseteq \{1, 2\}$.
- 4 Is All q (see only q) true in the model?
Answer: No, because $\{1, 2\} \not\subseteq \{4, 5, 6\}$.
- 5 Is All (see only p) (see only q) true in the model?
Answer: Yes, because $\{4, 6\} \subseteq \{4, 5, 6\}$.
- 6 Is All (see only q) (see only p) true in the model?
Answer: No, because $\{4, 5, 6\} \not\subseteq \{4, 6\}$.

$$\frac{}{\text{all } x \ x} \text{ AXIOM}$$

$$\frac{\text{all } x \ y \quad \text{all } y \ z}{\text{all } x \ z} \text{ BARBARA}$$

$$\frac{\text{all } x \ (r \ \text{only } y) \quad \text{all } y \ z}{\text{all } x \ (r \ \text{only } z)} \text{ ONLY}$$

$$\frac{\text{all } x \ y}{\text{all } (r \ \text{only } x) \ (r \ \text{only } y)} \text{ MONO}$$

We can use **either** (ONLY) or (MONO); they are inter-derivable.

GIVEN A SET Γ , WE DEFINE A MODEL $\mathcal{M} = \mathcal{M}_\Gamma$ IN SEVERAL STEPS.

We saw yesterday and Monday the preorder \leq on terms by

$$s \leq t \quad \text{iff} \quad \Gamma \vdash \text{all } s \ t.$$

We take M to be the set of all sets \mathcal{S} of terms which are **up-closed** in this preorder.

And then we define, for all unary atoms p and binary atoms r ,

$$\begin{aligned} \llbracket p \rrbracket &= \{ \mathcal{S} \in M : p \in \mathcal{S} \} \\ \llbracket r \rrbracket &= \{ (\mathcal{S}, \mathcal{T}) \in M \times M : \text{if } (r \text{ only } x) \in \mathcal{S}, \text{ then } x \in \mathcal{T} \} \end{aligned}$$

EXAMPLE: $\Gamma = \{\text{all } p \ q\}$

THIS TIME AS A SET WITH A SENTENCE IN $\mathcal{O}(\mathcal{RC})$.

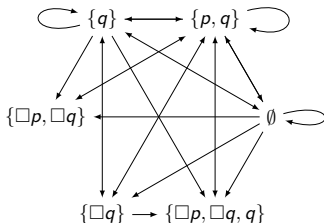
To simplify matters, we assume that the only unary atoms are p and q , and that the only binary atom is r .

The points in the canonical model are the sets \mathcal{S} of sentences with the property that for all n ,

if r only ^{n} $p = \Box^n p$ belongs to \mathcal{S} , then so does r only ^{n} $q = \Box^n q$.

This model is **uncountable**.

Here are six of its points, together with the arrows (interpreting r) between them.



We have written r only p as $\Box p$, and similarly for q .
What are the interpretations of p and q ?

RESULTS ON $\mathcal{O}(\mathcal{RC})$, AND A QUESTION

LEMMA (TRUTH LEMMA)

Let \mathcal{M} be the canonical model of some set Γ .
Then for all terms x ,

$$\llbracket t \rrbracket = \{S \in M : t \in S\}.$$

THEOREM (COMPLETENESS)

$\Gamma \vdash \varphi$ iff $\Gamma \models \varphi$.

THEOREM

This logic $\mathcal{O}(\mathcal{RC})$ has the finite model property:
if $\Gamma \not\models \varphi$, there is a finite counter-model.

RESULTS ON $\mathcal{O}(\mathcal{RC})$, AND A QUESTION

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QUERY

Can the size of the counter-model be taken to be a polynomial in the size of $\Gamma + \varphi$?