Dec. 8, Last class meeting

- MP2 on RL due
- 4th hour project due
  - Paper: your project, your approach, why, what you learned, how you would do it differently…
  - Code
  - I/O + analysis
  - Graded on the additional AI that you learned + presentation etc.

Reinforcement Learning (vs. Classical Planning)

- Robust
  - Fewer *a priori* assumptions (esp. actions)
  - Empirical model
  - Fit (via parameter adjustment) to the *observed* world
- Scaling difficulties
  - Propositional expressiveness
  - Complexity space / time (?)
  - States / Features (e.g., block positions)
- Markov assumption
  - Our world?
  - Implications for sensors & convergence
  - Discretizing may not respect Markov

Two Strips Operators for Move

MoveToBlock (x, y, z):

PC: Clr (x), Clr (z), On (x, y), Blk (x),
Blk (z), Diff (x, z), Diff (y, z)

Delete: On (x, y), Clr (z),
Add On (x, z), Clr (y)

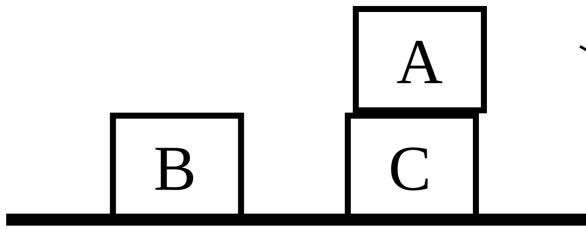
MoveToTable (x, y):

PC: Clr (x), On (x, y), Blk (x), Diff (y, Tbl)

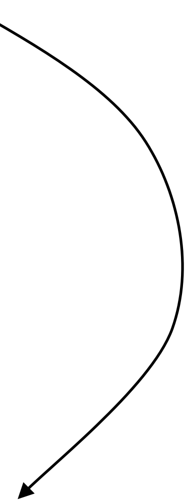
Delete: On (x, y)
Add: On (x, Tbl), Clr (y)

World Change

Initial State: Si

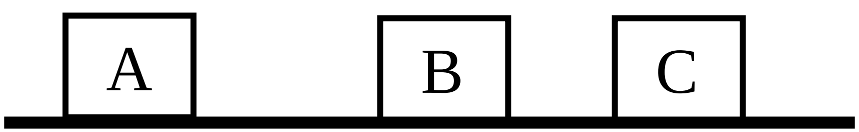


…
On(A, C)
...



MoveToTable (A, C)

State after MoveToTable (A, C) in Si



…
On(A, Tbl)
...

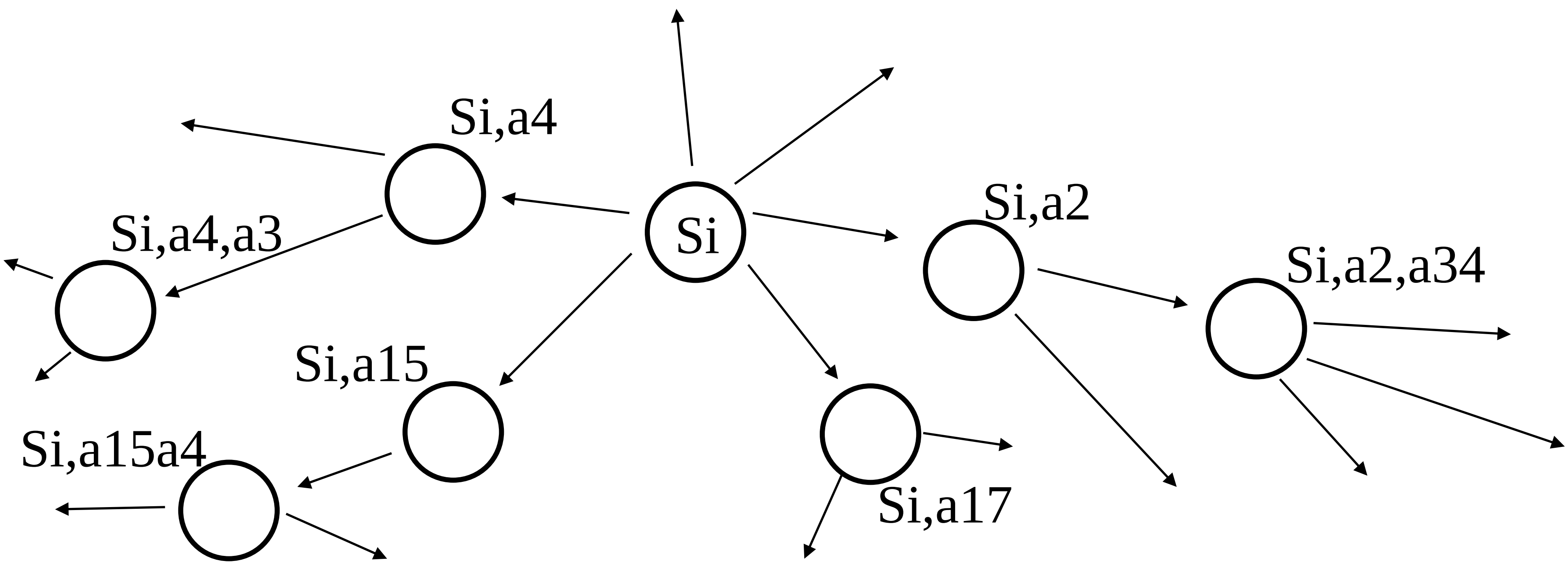
All Reachable Situations are Defined

Given: 1) the Initial State

2) Axioms of World Change (operator definitions)

Can be realized as predicate calculus theorem proving

$\Delta \equiv$ Initial State $\cup$ Operator Definitions



Knowledge Representation

- Planning (e.g., pickup)
  - purely analytic model (compare RL)
  - more expressive (can't learn)
  - relies heavily (exclusively) on priors
- More general than planning: reasoning about knowledge
- First order logic, Horn theories, description logics, …
- Logical (vs. statistical) inference
- Objects, Predicates, Functions, Variables, Quantifiers, Connectives

Reasoning = logical inference

- Model is analytic:
  - An Ontology
  - Declarative sentences
  - Inference procedure
- Prolog (Horn logic as prog lang)
- Deductive Databases
- Web 2.0 (describe content for machines)
- Computer games
- …

Logic, KR, KRR
(Knowledge Representation and Reasoning)

- Declarative (not procedural)
- Symbolic (not “sub-symbolic”)
- Well-defined componential semantics
- Interesting operations (e.g., inference) can be defined purely syntactically

- Does not naturally embrace uncertainty (this is its Achilles heel)

Inference

Apples are delicious things

Delicious things are edible

Therefore...

"I've eaten apples. I recall biting into a crisp McIntosh. The sweet juice in my mouth…certainly it was edible."

Or… "I've eaten apples. They *are* delicious, but they give me bad indigestion; they are *not* edible."

Philosophical / AI problem of "grounding"

Symbolic Logic offers a solution

Symbolic Inference

$A \Rightarrow B$

$B \Rightarrow C$

A

Therefore:

B

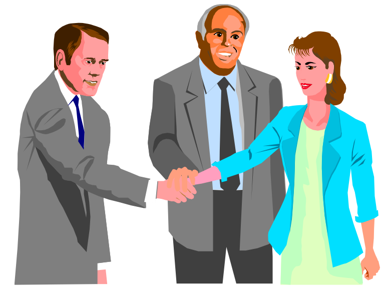
C

$A \Rightarrow C$

…

But what does "A" mean / stand for?

Universe / Universe of Discourse / Domain / ...



Objects are denoted by symbols:

Andy17 denotes

⇧

object constant symbol
constant symbol
object constant

Andy Smith
Age 23
Height 5’9”
...

For us, different object constants implies different objects and vice versa.

Mary Smith
Age 25
...

The symbol / object association is arbitrary:

Car54 denotes

Predicates / Relations are Denoted by Symbols

Married(Andy17, Car54)

Predicate Symbol

A particular relationship exists between the individuals

Predicates are n-ary

Meaning of a predicate is a (possibly infinite) set of n-tuples:
{(Joe23, Jill6), (Liz13, Fred972), …(Andy17, Car54)…}

Functions are Denoted by Symbols

Father-of(Andy17)

Function Symbol

Another way of denoting an individual i.e., John3

Functions are n-ary

Meaning of a function is a (possibly infinite) set of n+1 tuples:
{(Joe23, Fred972), (Liz13, John3), …(Andy17, John3)…}

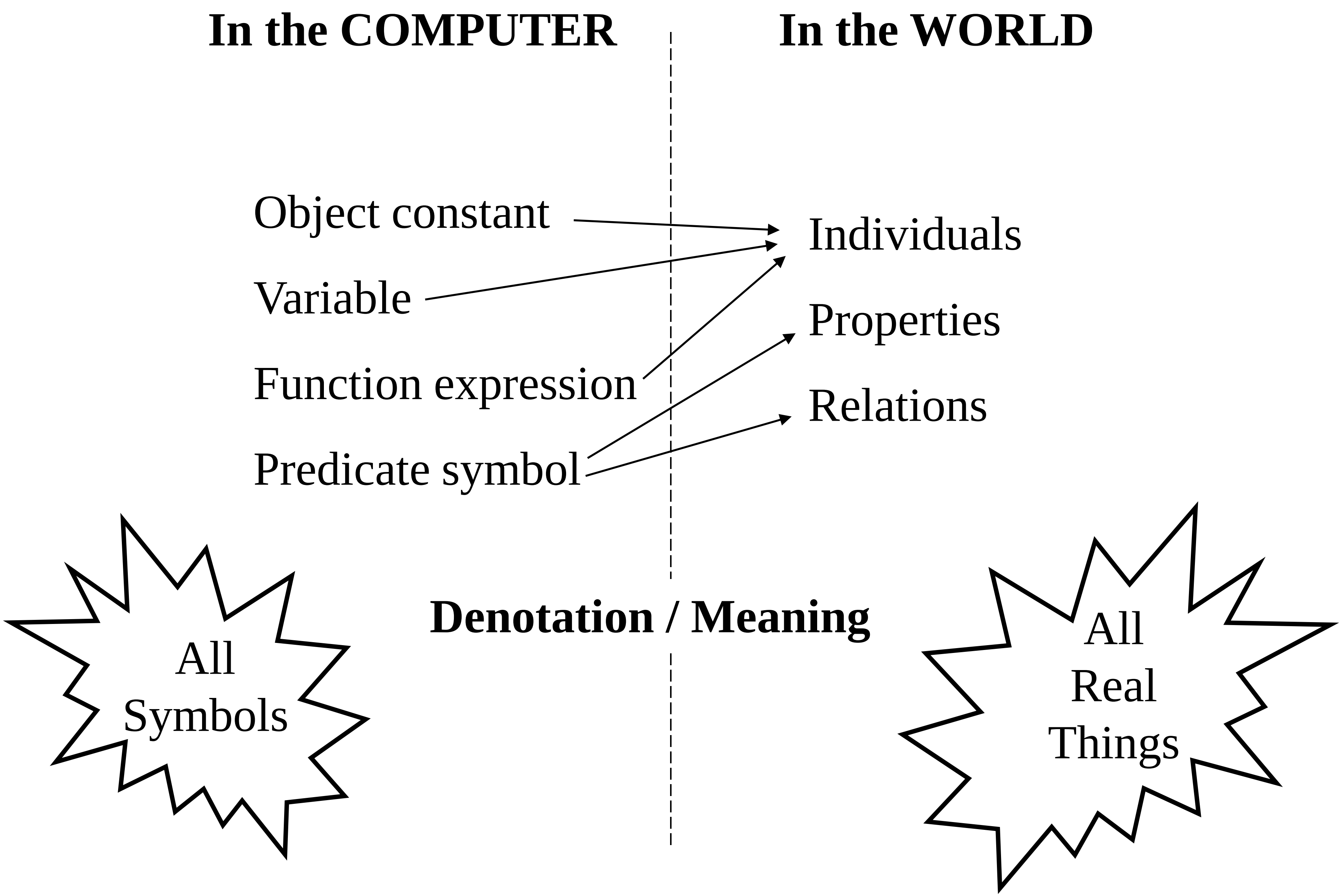
Variables - another type of symbol

- First Order
- Stand for individuals in the universe of discourse
- Not functions or relations
- Can be “free” or “bound”

“within the scope of a quantifier”
(NB: *NOT* a programming notion)

Important quantifiers

∃	**existential**	**“there exists”**
∀	**universal**	**“for all”**


In the COMPUTER
In the WORLD
Object constant
Variable
Function expression
Predicate symbol
Individuals
Properties
Relations
Denotation / Meaning
All Symbols
All Real Things

Logical Connectives

$\neg$	**negation**	**“not”**
$\wedge$	**conjunction**	**“and”**
$\vee$	**disjunction**	**“or”**
$\Rightarrow$	**implication**	**“implies”**
$\Leftrightarrow$	**equivalence**	**“if and only if”**

A *term* denotes an individual in the universe of discourse

- variable
- object constant
- function expression

A *function expression* is an n-ary function symbol with n terms as arguments

An *atom* (also atomic sentence, atomic WFF) is an n-ary predicate symbol with n terms as arguments

A *literal* is an atom or a negated atom

Well Formed Formulas WFFs

Atoms are WFFs

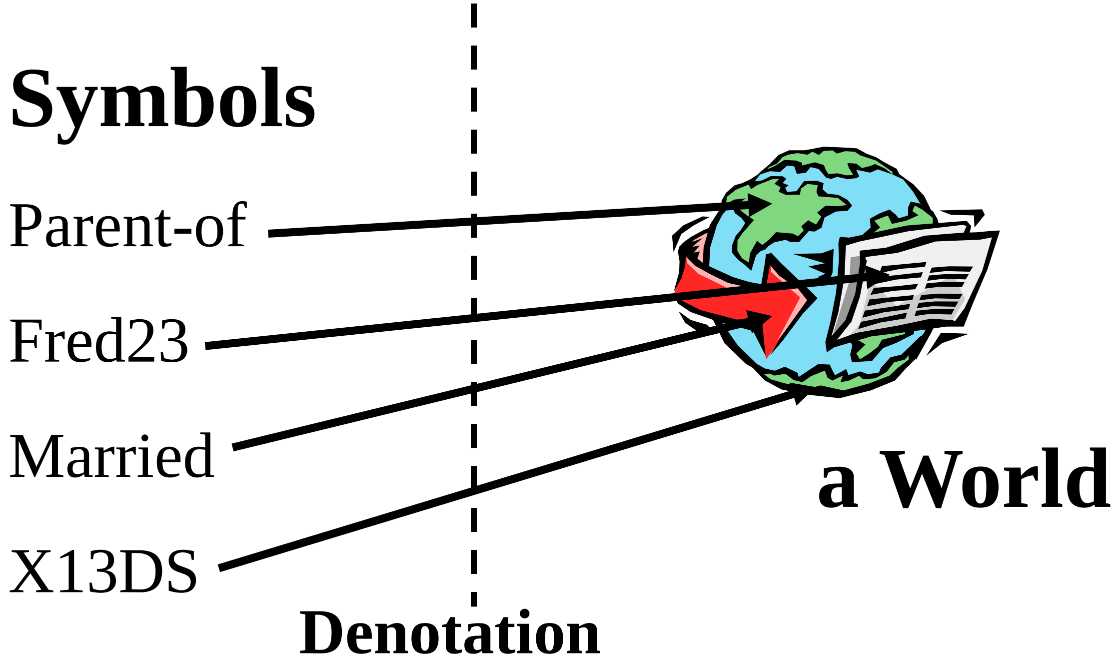
If Θ and Φ are WFFs then so are

$\forall x\ \Theta$	$\exists x\ \Theta$	$\neg\ \Theta$
$\Theta \wedge \Phi$	$\Theta \vee \Phi$	
$\Theta \Rightarrow \Phi$	$\Theta \Leftrightarrow \Phi$	

Logical implication $\Theta \Rightarrow \Phi$ is precisely $\neg\Theta \vee \Phi$
(*not* English implication!)

$\Theta \Leftrightarrow \Phi$ is precisely $(\Theta \Rightarrow \Phi) \wedge (\Phi \Rightarrow \Theta)$

$\vee$ “or” is inclusive



WFFs are *Truth Valuable* given a world and a denotational correspondence

WFF + denotation is a claim or assertion about the world

Claim holds or not (is true or false) depending on relations in the world

Examples

Some student is named “John”

$\exists x\ [Student(x) \wedge Name(x, \text{“John”})]$

Every student owns a computer

$\forall x\ [Student(x) \Rightarrow \exists y\ (Computer(y) \wedge Owns(x,y))]$

Scope of y

Scope of x

$\exists y\ [Computer(y) \wedge \forall x\ (Student(x) \Rightarrow Owns(x,y))]$

WFFs have different meanings

The English statement is ambiguous

Consider Representing Statistically

$$\forall x\ [\mathrm{Student}(x) \Rightarrow \exists y\ (\mathrm{Computer}(y) \wedge \mathrm{Owns}(x,y))]$$

- What are the random variables?
  (what are we modeling?)
- How is the probability distributed?
- How many distributions?
- How many students? How many computers?
- Note

More Examples

Birds fly.

Some birds fly.

Room 1404 Siebel is empty.

Some Ford is better than any Buick.

Someone on the basketball team is taller than anyone on the football team.

“Birds Fly”

$\forall x\ [\text{Bird}(x) \Rightarrow \text{Flies}(x)]$

$\forall x\ [B(x) \Rightarrow F(x)]$ where B means “is a bird”
and F means “can fly”

We can also think about the meaning as
“There are no birds that cannot fly”

$\neg\exists x\ [\text{Bird}(x) \wedge \neg\text{Flies}(x)]$

These are equivalent: the two predicate calculus sentences have the same meaning although they look quite different.

Some birds fly.

$\exists x$ [Bird(x) $\wedge$ Flies(x)]

Note: in logic "some" traditionally means "at least one"

Room 1404 Siebel is empty. [taken to mean empty of students]

Really Bad: P

Poor: Empty(Room1404SC)

Better: $\forall x$ [Student(x) $\Rightarrow$ Different(Location-of(x), Room1404SC)]

Still Better: $\forall x \forall y$ [(Student(x) $\wedge$ Location(y) $\wedge$ At(x,y)) $\Rightarrow$ Different(y, Room1404SC)]

Completely Wrong: (why?)

$\forall x$ [Student(x) $\Rightarrow$ At(x, $\neg$Room1404SC)]

NOTE: functions (like Location-of) are partial…

Some Ford is better than any Buick.

$\exists x\ [Ford(x) \wedge \forall y\ [Buick(y) \Rightarrow Better(x,y)]]$

Better(x,y) means “x is better than y”

Someone on the basketball team is taller than anyone on the football team.

$$\exists x\ [Member(x,BBallTeam) \wedge \\ \forall y\ \forall z\ \forall w\ [(Height(x,z) \wedge Member(y,FBallTeam) \wedge Height(y,w)) \\ \Rightarrow Greater(z,w)]]$$

Greater(x,y) means “x is larger than y”

"CS440 is my favorite class"

There is some amount that I like CS440
and I like all other classes less

$$\exists z\ \exists w\ [Class(w) \wedge Name(w,\text{“CS440”}) \wedge Likes(Me,w,z) \wedge \forall x\ \forall y\ \{[Class(x) \wedge Likes(Me,x,y) \wedge Different(x,w)] \Rightarrow Greater(z,y)\}]$$

Likes(a,b,c) means "a likes b by amount c"
Greater(a,b) means "a is larger than b"
(Class, Different, Me have their intuitive meanings)

There is no class that I like as much as CS440

(many others)

Semantics

- **There are many ways the world might be.**
- **For each, there are many distinct denotational correspondences.**
- **A *possible world*, for us, is a world and a denotation.**
- **There is some Universe of all possible worlds.**
- **The *meaning* of a WFF is the subset of possible worlds in which it holds.**

(Lecture & text use "possible world" for the more standard but less intuitive "interpretation")

SEMANTICS

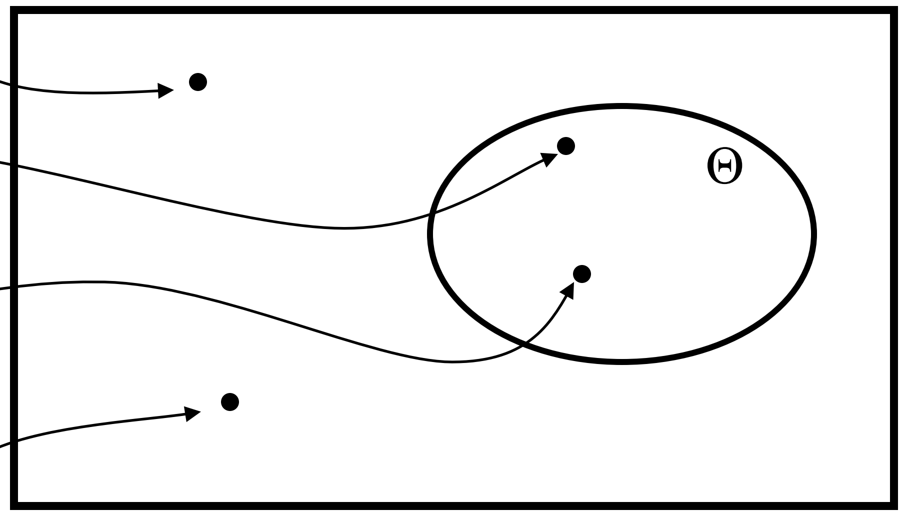
$$\Theta: \forall x\,[\text{Student}(x) \Rightarrow \text{Happy}(x)]$$

Intuitive meaning
in our world

Student means “is a student”
Happy means “is happy”
and all students are joyful in this world

Student means “is a giraffe”
Happy means “has a short neck”
and there are no giraffes in this world

Student means “can drive”
Happy means “can swim”
in our world



Universe of Possible Worlds

A WFF is

Satisfiable if it holds

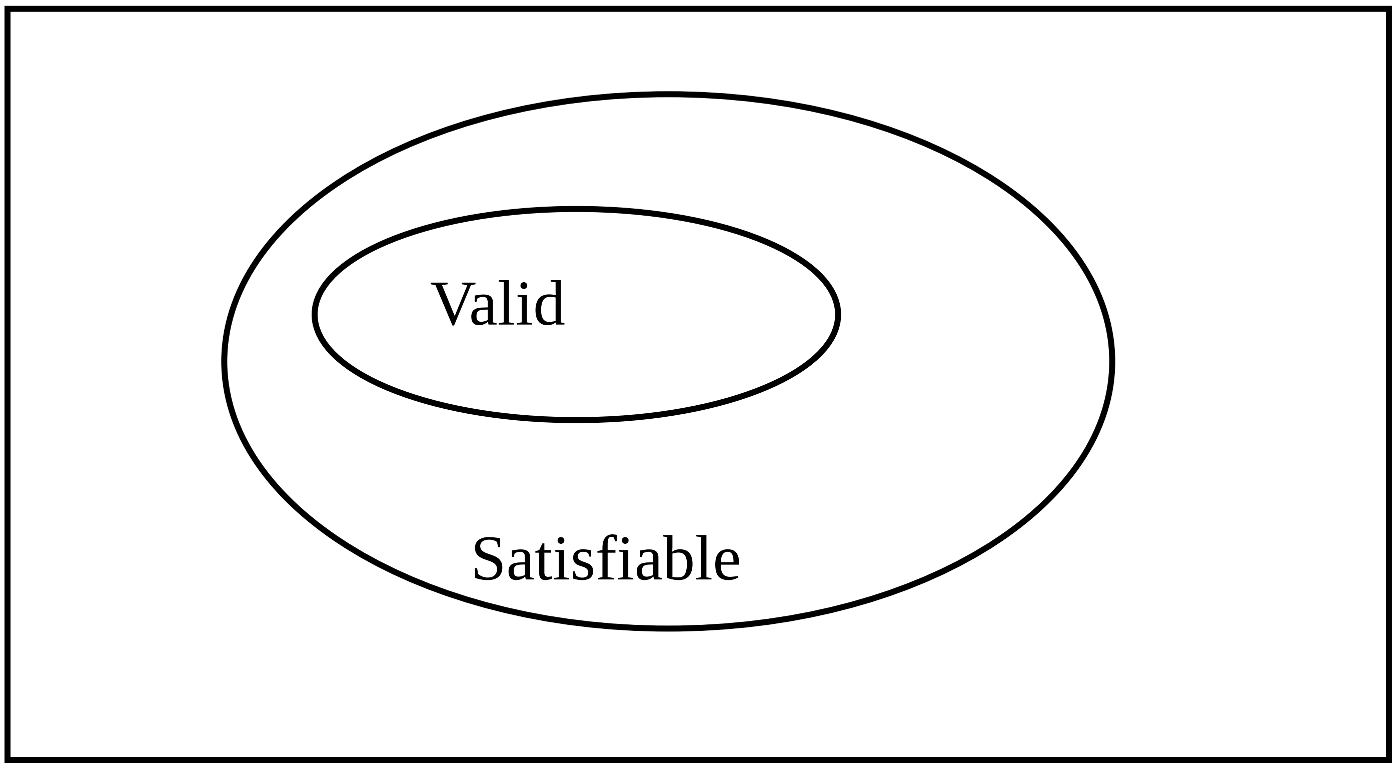
for **some** denotational correspondence
and **some** world

Valid if it holds

for **any** denotational correspondence
and **any** world

In Venn diagrams (actually Euler circles)…

Validity and Satisfiability



All WFFs

(**not** universe of possible worlds!)

Can you give a WFF that is

1. Valid	$P \vee \neg P$ $\quad R \Rightarrow R$
2. Satisfiable	P
3. Not valid	P
4. Not satisfiable	$P \wedge \neg P$
5. Satisfiable but not valid	P
6. Valid but not satisfiable	Not possible