

# Lecture 5 - Propositions and Inference

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Readings: Poole & Mackworth 2nd ed. chapter 5.1-5.3, and  
13.1-13.2

Two methods for solving problems:

- Procedural
  - ▶ devise an algorithm
  - ▶ program the algorithm
  - ▶ execute the program
- Declarative
  - ▶ identify the knowledge needed
  - ▶ encode the knowledge in a representation (knowledge base - KB)
  - ▶ use logical consequences of KB to solve the problem

Two methods for solving problems:

- Procedural
  - ▶ “how to” knowledge
  - ▶ programs
  - ▶ meaning of symbols is meaning of computation
  - ▶ languages: C,C++,Java ...
- Declarative
  - ▶ descriptive knowledge
  - ▶ databases
  - ▶ meaning of symbols is meaning in world
  - ▶ languages: propositional logic, Prolog, relational databases, ...

A logic consists of

- syntax: what is an acceptable sentence?
- semantics: what do the sentences and symbols mean?
- proof procedure: how do we construct valid proofs?

A proof: a sequence of sentences derivable using an inference rule

and ( <i>conjunction</i> )	$\wedge$
or ( <i>disjunction</i> )	$\vee$
not ( <i>negation</i> )	$\neg$
if ... then ... ( <i>implication</i> )	$\rightarrow$
... if and only if ...	$\leftrightarrow$

# Implication Truth Table

A	B	$A \rightarrow B$
F	F	T
F	T	T
T	F	F
T	T	T

(A) (B)  
If it rains, then I will carry an umbrella

# Implication Truth Table

A	B	$A \rightarrow B$
F	F	T
F	T	T
T	F	F
T	T	T

(A) (B)  
If it rains, then I will carry an umbrella  
If you don't study, then you will fail

# Implication Truth Table

$A$	$B$	$A \rightarrow B$	$A \wedge \neg B$	$\neg(A \wedge \neg B)$	$\neg A \vee B$
F	F	T	F	T	T
F	T	T	F	T	T
T	F	F	T	F	F
T	T	T	F	T	T

(A)                      (B)  
no rain or I will carry an umbrella  
study or you will fail



# If and only if Truth Table

A	B	$A \leftrightarrow B$
F	F	T
F	T	F
T	F	F
T	T	T

$$A \leftrightarrow B \equiv (A \rightarrow B) \wedge (B \rightarrow A)$$

# De Morgan's Laws

$$\mathbf{A} \vee \mathbf{B} \equiv \neg(\neg\mathbf{A} \wedge \neg\mathbf{B})$$

it rains OR I play football

not true that ( it doesn't rain AND I don't play football )

$$\mathbf{A} \wedge \mathbf{B} \equiv \neg(\neg\mathbf{A} \vee \neg\mathbf{B})$$

I'm a politician AND I lie

not true that ( I'm not a politician OR I tell the truth )

# Modus Ponens

<b>A</b>	<b>B</b>	<b><math>A \rightarrow B</math></b>	<b><math>(A \rightarrow B) \wedge A</math></b>	<b><math>((A \rightarrow B) \wedge A) \rightarrow B</math></b>
F	F	T	F	T
F	T	T	F	T
T	F	F	F	T
T	T	T	T	T

Modus Ponens is a **Tautology**

If it's raining then the grass is wet

it's raining

therefore the grass is wet

# Modus Tolens

<b>A</b>	<b>B</b>	<b><math>A \rightarrow B</math></b>	<b><math>(A \rightarrow B) \wedge \neg B</math></b>	<b><math>((A \rightarrow B) \wedge \neg B) \rightarrow \neg A</math></b>
F	F	T	T	T
F	T	T	F	T
T	F	F	F	T
T	T	T	F	T

Modus Tolens is a **Tautology**

If it's raining then the grass is wet

the grass is not wet

therefore it's not raining

# Modus Bogus

<b>A</b>	<b>B</b>	<b><math>A \rightarrow B</math></b>	<b><math>(A \rightarrow B) \wedge B</math></b>	<b><math>((A \rightarrow B) \wedge B) \rightarrow A</math></b>
F	F	T	F	T
F	T	T	T	F
T	F	F	F	T
T	T	T	T	T

Modus Bogus is not a **Tautology**

If it's raining then the grass is wet

the grass is wet

therefore its raining

- $\{X\}$  is a set of *statements*
- A set of truth assignments to  $\{X\}$  is an *interpretation*
- A *model* of  $\{X\}$  is an interpretation that makes  $\{X\}$  true.
- We say that the world in which these truth assignments hold is a *model* (a verifiable *example*) of  $\{X\}$ .
- $\{X\}$  is *inconsistent* if it has no *model*

A statement,  $A$ , is a logical consequence of a set of statements  $\{X\}$ , if  $A$  is true in every *model* of  $\{X\}$ .

If, for every set of truth assignments that hold for  $\{X\}$  (for every *model* of  $\{X\}$ ), some other statement ( $A$ ) is always true, then this other statement is a *logical consequence* of  $\{X\}$

An argument is **valid** if any of the following is true:

- the conclusions are a logical consequence of the premises.
- the conclusions are true in every model of the premises
- there is **no** situation in which the premises are all true, but the conclusions are false.
- argument  $\rightarrow$  conclusions is a *tautology* (always true)

(these four statements are identical)



# Arguments and Models

P1: If I play hockey , then I'll score a goal if the goalie is not good

P2: If I play hockey , the goalie is not good

D: Therefore, if I play hockey , I'll score a goal

P: I play hockey

C: I'll score a goal

H: the goalie is good

$$P1 : P \rightarrow (\neg H \rightarrow C) \quad P2 : P \rightarrow \neg H$$

$$D : P \rightarrow C$$

$P$	$C$	$H$	$\neg H \rightarrow C$	$P1$	$P2$	$D$
F	F	F	F	T	T	T
F	F	T	T	T	T	T
F	T	F	T	T	T	T
F	T	T	T	T	T	T
T	F	F	F	F	T	F
T	F	T	T	T	F	F
T	T	F	T	T	T	T
T	T	T	T	T	F	T

# Arguments and Models

P1: If I play hockey , then I'll score a goal if the goalie is not good

P2: If I play hockey , the goalie is not good

D: Therefore, if I play hockey , I'll score a goal

P: I play hockey

C: I'll score a goal

H: the goalie is good

$$P1 : P \rightarrow (\neg H \rightarrow C) \quad P2 : P \rightarrow \neg H$$

$$D : P \rightarrow C$$

<i>P</i>	<i>C</i>	<i>H</i>	$\neg H \rightarrow C$	<i>P1</i>	<i>P2</i>	<i>D</i>
F	F	F	F	T	T	T
F	F	T	T	T	T	T
F	T	F	T	T	T	T
F	T	T	T	T	T	T
T	F	F	F	F	T	F
T	F	T	T	T	F	F
T	T	F	T	T	T	T
T	T	T	T	T	F	T

# Arguments and Models

$P$	$C$	$H$	$\neg H \rightarrow C$	$P1$	$P2$	$D$
F	F	F	F	T	T	T
F	F	T	T	T	T	T
F	T	F	T	T	T	T
F	T	T	T	T	T	T
T	F	F	F	F	T	F
T	F	T	T	T	F	F
T	T	F	T	T	T	T
T	T	T	T	T	F	T

Each row is an *interpretation*: an assignment of T/F to each proposition

In all the green lines, the premises are true:

these interpretations are *models* of  $P1$  and  $P2$ .

Every *model* of  $P1$  and  $P2$  is a *model* of  $D$ .

Therefore,  $D$  is a *logical consequence* of  $P1$  and  $P2$ :

$$P1, P2 \models D.$$

# Logical Consequence

P1: Elvis is Dead

P2: Elvis is Not Dead

D: Therefore, Gerry is Alive

Is this argument valid?

# Logical Consequence

P1: Elvis is Dead

P2: Elvis is Not Dead

D: Therefore, Gerry is Alive

Is this argument valid?

Yes!

E: Elvis is Alive

G: Gerry is Alive

E	$\neg E$	G
F	T	F
F	T	T
T	F	F
T	F	T

An argument is **valid** if there is **no** situation in which the premises are all true, but the conclusions are false.

But here, there is **no** model of the premises, so the argument is valid.

Given a knowledge base, we want to prove things that are true.  
We can use

- Truth Table
- Natural Deduction
- Semantic Tableaux
- Axiomatic Logic (Modus Ponens)  
 $((\mathbf{A} \rightarrow \mathbf{B}) \wedge \mathbf{A}) \rightarrow \mathbf{B}$
- Resolution Refutation (Reductio Ad Absurdum)  
 $(\neg \mathbf{A}) \wedge \dots \wedge \dots \rightarrow \perp) \rightarrow \mathbf{A}$

- A **KB** is a set of axioms
- A **proof procedure** is a way of Proving Theorems
- $KB \vdash g$  means  $g$  can be **derived** from  $KB$  using the proof procedure
- If  $KB \vdash g$ , then  $g$  is a **Theorem**
- A proof procedure is **sound**:  
if  $KB \vdash g$  then  $KB \models g$ .
- A proof procedure is **complete**:  
if  $KB \models g$  then  $KB \vdash g$ .
- Two types of proof procedures:  
**bottom up** and **top down**

- we assume a *closed world*
  - ▶ the agent knows everything (or can prove everything)
  - ▶ if it can't prove something: must be false
  - ▶ *negation as failure*
- other option is an *open world*:
  - ▶ the agent doesn't know everything
  - ▶ can't conclude anything from a lack of knowledge



also known as **forward chaining** - start from facts and use rules to generate all possible atoms

```
rain ← clouds ∧ wind.  
clouds ← humid ∧ cyclone.  
clouds ← near_sea ∧ cyclone.  
wind ← cyclone.  
near_sea.  
cyclone.
```

also known as **forward chaining** - start from facts and use rules to generate all possible atoms

```
rain ← clouds ∧ wind.  
clouds ← humid ∧ cyclone.  
clouds ← near_sea ∧ cyclone.  
wind ← cyclone.  
near_sea.  
cyclone.  
{near_sea, cyclone }
```

also known as **forward chaining** - start from facts and use rules to generate all possible atoms

```
rain ← clouds ∧ wind.  
clouds ← humid ∧ cyclone.  
clouds ← near_sea ∧ cyclone.  
wind ← cyclone.  
near_sea.  
cyclone.  
{near_sea,cyclone }  
{near_sea ,cyclone ,wind }
```

also known as **forward chaining** - start from facts and use rules to generate all possible atoms

```
rain ← clouds ∧ wind.  
clouds ← humid ∧ cyclone.  
clouds ← near_sea ∧ cyclone.  
wind ← cyclone.  
near_sea.  
cyclone.  
{near_sea,cyclone }  
{near_sea ,cyclone ,wind }  
{near_sea ,cyclone ,wind ,clouds }
```

also known as **forward chaining** - start from facts and use rules to generate all possible atoms

```
rain ← clouds ∧ wind.
```

```
clouds ← humid ∧ cyclone.
```

```
clouds ← near_sea ∧ cyclone.
```

```
wind ← cyclone.
```

```
near_sea.
```

```
cyclone.
```

```
{near_sea,cyclone }
```

```
{near_sea ,cyclone ,wind }
```

```
{near_sea ,cyclone ,wind ,clouds }
```

```
{near_sea ,cyclone ,wind ,clouds ,rain }
```

```
C := {};  
repeat  
  select  $r \in KB$  such that  
    ·  $r$  is  $h \leftarrow b_1 \wedge \dots \wedge b_m$   
    ·  $b_i \in C \quad \forall \quad i$   
    ·  $h \notin C$   
   $C := C \cup \{h\}$   
until no more clauses can be selected
```

Sound and Complete

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.



# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  wind

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  cyclone

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  cyclone

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  cyclone

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone

yes  $\leftarrow$  cyclone

# Top-Down Proof

start from query and work backwards

rain  $\leftarrow$  clouds  $\wedge$  wind.

clouds  $\leftarrow$  humid  $\wedge$  cyclone.

clouds  $\leftarrow$  near\_sea  $\wedge$  cyclone.

wind  $\leftarrow$  cyclone.

near\_sea.

cyclone.

yes  $\leftarrow$  rain.

yes  $\leftarrow$  clouds  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  wind

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone  $\wedge$  cyclone

yes  $\leftarrow$  near\_sea  $\wedge$  cyclone

yes  $\leftarrow$  cyclone

yes  $\leftarrow$

```
solve( $q_1 \wedge \dots \wedge q_k$ ):  
   $ac := \text{"yes"} \leftarrow q_1 \wedge \dots \wedge q_k$   
  repeat  
    select a conjunct  $q_i$  from body of  $ac$   
    choose a clause  $C$  from KB with  $q_i$  as head  
    replace  $q_i$  in body of  $ac$  by body of  $C$   
  until  $ac$  is an answer
```

**select:** “don’t care nondeterminism”

If one doesn’t give a solution, no point trying others!

any one will do, but be careful: some selections will lead more quickly to solutions!

**choose:** “don’t know nondeterminism”

if one doesn’t give a solution, others may

have to do them all: can determine complexity of the problem. ▸

- A proof procedure gives us a method for deriving theorems
- Therefore, given a knowledge base of assumptions, we can 'prove' things and know they are tautologies (they are logical consequences of our knowledge base)

but ....

The method is difficult and requires some know-how - how could we make it work more automatically?



# Conjunctive Normal Form

A well-formed formula is in *conjunctive normal form* (CNF) if it is a conjunction of disjunctions of atoms.

$$(p_1 \vee p_2) \wedge (p_3 \vee p_4 \vee p_5) \wedge (p_6 \vee p_7 \vee \dots) \dots \wedge (p_{n-1} \vee p_n)$$

Convert a propositional formula to CNF:

1. Eliminate  $\leftrightarrow$  using  $A \leftrightarrow B \equiv (A \rightarrow B) \wedge (B \rightarrow A)$
2. Eliminate  $\rightarrow$  using  $A \rightarrow B \equiv \neg A \vee B$
3. Use deMorgan's laws to push  $\neg$  into atoms
4. Use  $\neg\neg A \equiv A$  to eliminate double negatives
5. use distributive law to complete

$$A \vee (B \wedge C) \equiv (A \vee B) \wedge (A \vee C)$$

write

$$(p_1 \vee p_2) \wedge (p_3 \vee p_4 \vee p_5) \wedge (p_6 \vee p_7 \vee \dots) \dots \wedge (p_{n-1} \vee p_n)$$

as

$$\{\{p_1, p_2\}, \{p_3, p_4, p_5\}, \{p_6, p_7, \dots\}, \dots, \{p_{n-1}, p_n\}\}$$

# Conjunctive Normal Form - Example 1

Refutation of Modus Ponens

$$A \wedge (A \rightarrow B) \vdash B$$

show a contradiction  $\perp$ : means “false”

If our refutation leads to a **contradiction**, it must be “false”, so the conclusion must be true

$$A \wedge (A \rightarrow B) \wedge \neg B \vDash \perp$$

1.  $A \wedge (\neg A \vee B) \wedge (\neg B)$
2.  $\{\{A\}, \{\neg A, B\}, \{\neg B\}\}$

can already tell this is false since  $A$  must be true, so  $B$  must be true, but  $B$  must be false

We will demonstrate using **resolution** on slide 28

## Conjunctive Normal Form - Example 2

Transitivity of Implication

$$((A \rightarrow B) \wedge (B \rightarrow C)) \rightarrow (A \rightarrow C)$$

try to show a contradiction

$$(A \rightarrow B) \wedge (B \rightarrow C) \wedge \neg(A \rightarrow C) \models \perp$$

1.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge \neg(\neg A \vee C)$
2.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge (\neg\neg A \wedge \neg C)$
3.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge A \wedge \neg C$
4.  $\{\{\neg A, B\}, \{\neg B, C\}, \{A\}, \{\neg C\}\}$

- A complementary pair of propositions is  $p_i, \neg p_i$
- Can show that two clauses with a complementary pair :  
 $\{\{A, B\}, \{C, \neg B\}\} \equiv \{\{A, B\}, \{C, \neg B\}, \{A, C\}\}$
- That is, since  $B$  and  $\neg B$  cannot both be true, one of  $A$  or  $C$  has to be true, otherwise the whole formula is false
- Therefore, we can “resolve”  $\{A, B\}, \{C, \neg B\}$  into  $\{A, C\}$
- This means that  $\{A, C\}$  is true whenever  $\{A, B\}, \{C, \neg B\}$  is true
- So we can *add*  $\{A, C\}$  to the statement without changing the truth value
- $\{\{A\}, \{\neg A\}\}$  resolves to  $\perp$

- Proof by *resolution refutation*: deny the conclusions and show a resolution to  $\perp$ .
- Resolve clauses - adds new clauses that are true whenever the existing clauses are true
- If you can find a contradiction, then
  - ▶ the existing clauses cannot all be true
  - ▶ If the premises are all true, the refutation of the conclusion **must** be false,
  - ▶ so the argument is valid
- If you cannot find a contradiction after resolving all clauses
  - ▶ the refutation of the conclusion **must** be true
  - ▶ so the argument is invalid

# Resolution - Example 1

Refutation of Modus Ponens

$$A \wedge (A \rightarrow B) \vdash B$$

show a contradiction

$$A \wedge (A \rightarrow B) \wedge \neg B \models \perp$$

1.  $A \wedge (\neg A \vee B) \wedge (\neg B)$
2.  $\{\{A\}, \{\neg A, B\}, \{\neg B\}\}$
3.  $\{\{A\}, \{\neg A, B\}, \{B\}, \{\neg B\}\}$
4.  $\perp$

## Resolution - Example 2

Transitivity of Implication (again)

$$((A \rightarrow B) \wedge (B \rightarrow C)) \rightarrow (A \rightarrow C)$$

try to show a contradiction

$$(A \rightarrow B) \wedge (B \rightarrow C) \wedge \neg(A \rightarrow C) \models \perp$$

1.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge \neg(\neg A \vee C)$
2.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge (\neg\neg A \wedge \neg C)$
3.  $(\neg A \vee B) \wedge (\neg B \vee C) \wedge A \wedge \neg C$
4.  $\{\{\neg A, B\}, \{\neg B, C\}, \{A\}, \{\neg C\}\}$
5.  $\{\{\neg A, B\}, \{\neg B, C\}, \{\neg A, C\}, \{A\}, \{\neg C\}\}$
6.  $\{\{\neg A, B\}, \{\neg B, C\}, \{\neg A, C\}, \{A\}, \{C\}, \{\neg C\}\}$
7.  $\perp$

## Resolution - Example 3

P1: If I play hockey , then I'll score a goal if the goalie is not good

P2: If I play hockey , the goalie is not good

D: if I play hockey , I'll score a goal

P: I play hockey , C: I'll score a goal , H: the goalie is good

$P1 : P \rightarrow (\neg H \rightarrow C)$

$P2 : P \rightarrow \neg H$

$D : P \rightarrow C$

test (refutation of D):  $P1 \wedge P2 \wedge \neg D$

$(P \rightarrow (\neg H \rightarrow C)) \wedge (P \rightarrow \neg H) \wedge \neg(P \rightarrow C)$

$(\neg P \vee (\neg H \rightarrow C)) \wedge (\neg P \vee \neg H) \wedge \neg(\neg P \vee C)$

$(\neg P \vee (\neg\neg H \vee C)) \wedge (\neg P \vee \neg H) \wedge \neg(\neg P \vee C)$

$(\neg P \vee \neg\neg H \vee C) \wedge (\neg P \vee \neg H) \wedge (\neg\neg P \wedge \neg C)$

$(\neg P \vee H \vee C) \wedge (\neg P \vee \neg H) \wedge (P) \wedge (\neg C)$

$\{\{\neg P, H, C\}, \{\neg P, \neg H\}, \{P\}, \{\neg C\}\}$

$\{\{\neg P, H, C\}, \{\neg P, \neg H\}, \{\neg P, C\}, \{P\}, \{\neg C\}\}$

$\{\{\neg P, H, C\}, \{\neg P, \neg H\}, \{\neg P, C\}, \{P\}, \{C\}, \{\neg C\}\}$

⊥



Many problems can be formulated as a CNF

- Satisfiability
- Logic circuits
- Gene decoding
- Scheduling
- Air traffic control
- ...

# Constraint Satisfaction as CNF

- A CSP variable  $Y$  with domain  $\{v_1, \dots, v_k\}$  can be converted into  $k$  Boolean variables  $\{Y_1, \dots, Y_k\}$  where  $Y_i$  is true when  $Y$  has value  $v_i$  and false otherwise.
- Thus,  $k$  atoms  $y_1, \dots, y_k$  are used to represent the CSP variable
- Constraints:
  - ▶ exactly one of  $y_1, \dots, y_k$  must be true:
    - ▶  $y_i$  and  $y_j$  cannot both be true when  $i \neq j$ :  $\neg y_i \vee \neg y_j$  for  $i < j$
    - ▶ at least one of the  $y_i$  must be true:  $y_1 \vee \dots \vee y_k$
  - ▶ There is a clause for each false assignment in each constraint that specifies which assignments are not allowed.
  - ▶ Thus, if there are two variables  $Y$  and  $Z$ , and a constraint  $Y \neq Z$ , then we have clauses  $\neg y_i \vee \neg z_i$  for all  $i$  (Assuming  $Y$  and  $Z$  have the same domains).

# Constraint Satisfaction as CNF

Example Delivery robot: activities  $a, b$ , times  $1, 2, 3, 4$ .

constraints :

$$(A \neq 2) \wedge (B \neq 1) \wedge (A < B)$$

We have two 8 variables in the CNF:

$$a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$$

where  $a_i$  means  $A = i$  is true and  $b_i$  means  $B = i$  is true.

Constraints saying that  $A$  (and  $B$ ) must be exactly one value:

$$\neg a_i \vee \neg a_j \quad \text{for } i < j \qquad a_1 \vee a_2 \vee a_3 \vee a_4$$

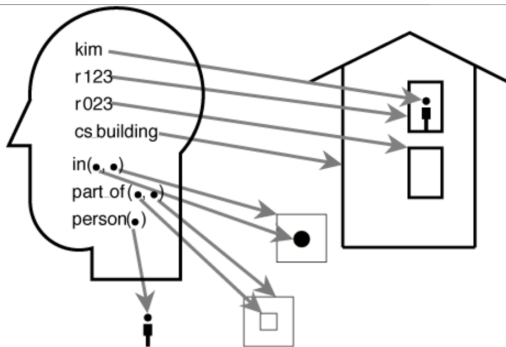
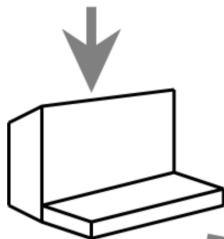
$$\neg b_i \vee \neg b_j \quad \text{for } i < j \qquad b_1 \vee b_2 \vee b_3 \vee b_4$$

Domain constraints  $\neg a_2$  and  $\neg b_1$

The binary constraint  $A < B$  has one  $\neg(a_i \wedge b_j)$  for all  $j \leq i$

# Beyond propositions: Individuals and Relations

$in(kim, r123).$   
 $part\_of(r123\ cs\_building).$   
 $in(X, Y) \leftarrow$   
 $part\_of(Z, Y) \wedge$   
 $in(X, Z).$



$in(kim, cs\_building)$

- Symbols: **M,I,U**
- Axiom: **MI**
- Rules:
  - ▶ if  $xI$  is a theorem, so is  $xIU$
  - ▶  $Mx$  is a theorem, so is  $Mxx$
  - ▶ in any theorem, **III** can be replaced by **U**
  - ▶ **UU** can be dropped from any string
- Starting from **MI**, can you generate **MU**? (use top-down or bottom-up)

## Next:

- Planning under certainty (Poole & Mackworth 2nd ed. Chapter 6.1-6.4)
- Supervised Learning (Poole & Mackworth 2nd ed. Chapter 7.1-7.6)