CSC242: Introduction to Artificial Intelligence

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Lecture 2.2

Please put away all electronic devices

Constraint Satisfaction Problem (CSP)

- X: Set of variables $\{X_1, ..., X_n\}$
- D: Set of A dimains of $\{$ ct B $\{$ $\{$ $\}$ $\}$
 - Each D_i : https://tutorcs.com Set of values $\{v_1, ..., v_k\}$
- C: Set of constraints $\{C_1, ..., C_m\}$
- Solution: Assign to each X_i a value from D_i such that all the C_j are satisfied

Factored Representation

- Splits a state into factors (attributes, features, variables) that can have values

 https://tutorcs.com
- Factored states more or less similar (unlike atomic states)
- Can also represent uncertainty (don't know the value of some attribute)

Backtracking Search for CSPs

- DFS search through the space of assignments

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- · Assign one variable at a time
- Because the representation of CSPs is standardized, no need to supply initial state, actions, transition model, or goal test!
- Early pruning of inconsistent states

Constraint Propagation

- Using the constraints to reduce the set of legal values of a variable, which can in Assignment Project Exam Help turn reduce the legal values of another variable, and so on WeChat; estutores
- Not a search process!
- Part of state update in state-space search
- A type of <u>inference</u>: making implicit information explicit

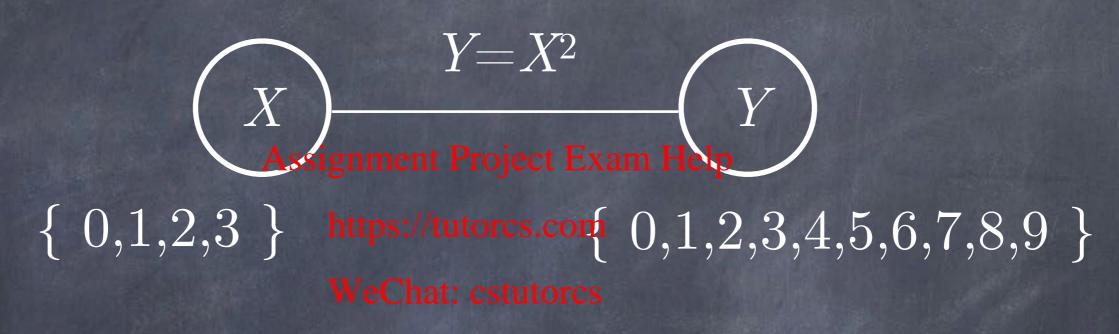
Constraint Propagation

- Node consistency:
 - Propagate una projeconstraints (once)
- Arc consistehttps://tutorcs.com
 - Propagate binary constraints
 - AC-3 algorithm

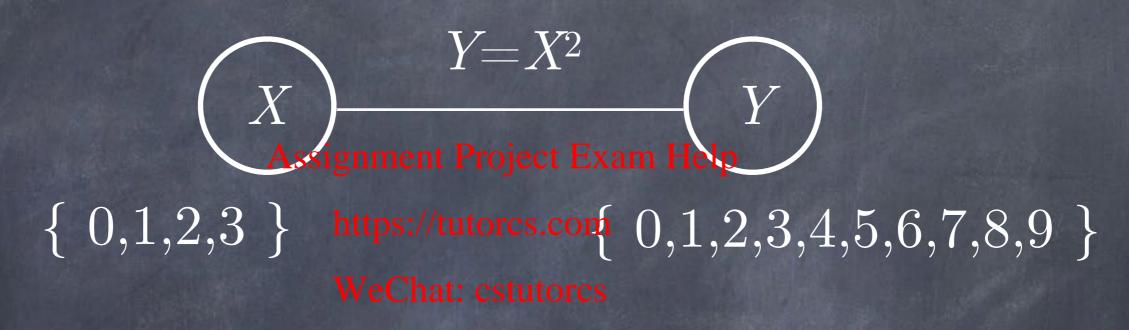
possible assignments: $10 \times 10 = 100$

$$\begin{array}{c} Y = X^2 \\ X \\ Assignment Project Exam Help \\ \\ \{ \ 0.1.2.3.4.5.6.7.8 \ \text{hgps} \} \text{/tutores.com} \\ 0.1.2.3.4.5.6.7.8.9 \ \} \end{array}$$

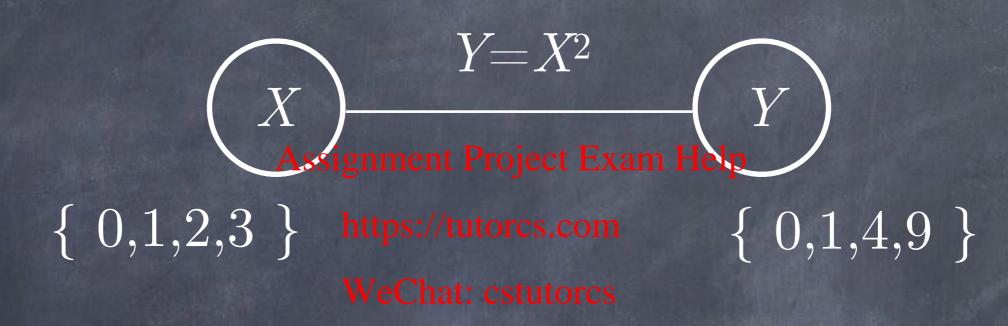
Make X arc-consistent with respect to Y



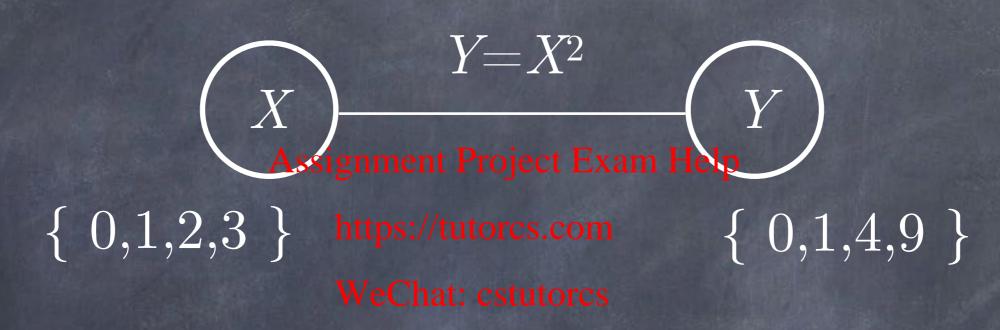
X arc-consistent with respect to Y



Make Y arc-consistent with respect to X



Y arc-consistent with respect to X



X and Y arc-consistent

$$Y = X^2$$

$$X = Y$$

$$X = Y$$

$$\{ 0,1,2,3 \} \text{ https://tutorcs.com } \{ 0,1,4,9 \}$$

$$\text{WeChat: cstutorcs}$$

X and Y arc-consistent

possible assignments: $4 \times 4 = 16$

AC-3

```
boolean revise(csp, i, j) {
boolean AC3(csp) {
 Set queue = all arcs in csp
                                  boolean changed = false
 <i,j> = queue.removeFirst() boolean ok = false
   if (revise(csp, i,Ais)) nment Project Example th vj in Dj {
     if Di is empty {
                                       if (<vi,vj> satisfies Cij )
       return false <a href="https://tutorcs.com">https://tutorcs.com</a> ok = true
     foreach k in neighbors (1) { cstutorcs
       add <k,i> to queue
                                      if (!ok) {
                                        delete vi from Di
                                        changed = true
 return true
                                    return changed
```

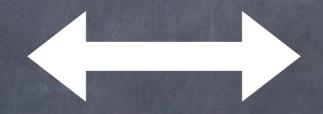
AC-3 Analysis

- CSP with n variables, domain size O(d), c constraints (arcs) c roject Exam Help
- Each arc cantibe/inserted in the queue at most d times We Chat: cstutores
- ullet Checking a single arc takes $O(d^2)$ time
- Total time: $O(cd^3)$
 - ullet Independent of n

Constraint Propagation

• "After constraint propagation, we are left with a CSP that is equivalent to the original CSP—they both have the same solutions—but the new CSP will in most cases be faster to search because its variables have smaller domains."

Constraint
Propagation
(inference)



State-Space Search

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Interleaving Search and Inference

• After each choice during search, we can perform inference to reduce future search

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Interleaving Search and Inference

- CSP:
- Variables
- Domains
- Constraints

```
Inconsistent?
    Node Consistency -
Assignment Project Exam Help
        https://tutorcs.com
                                  Inconsistent?
Arc Consistencycs(AC-3)
          Solved? Yes Done!
    Assign a variable — Backtrack No
```

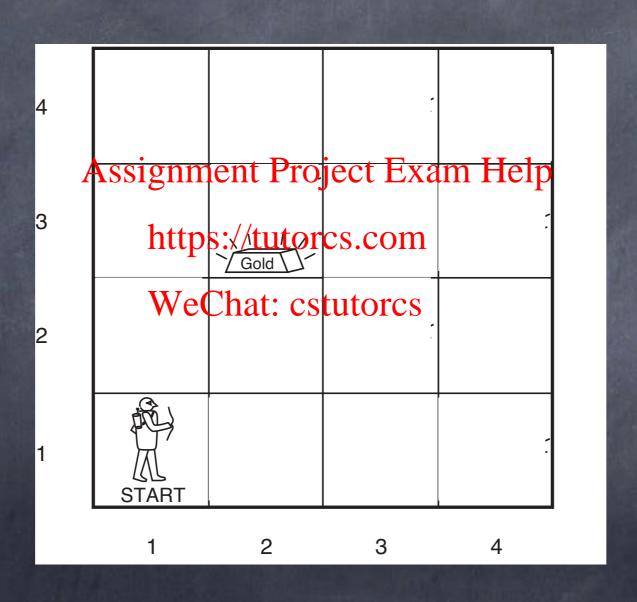
Constraint Satisfaction

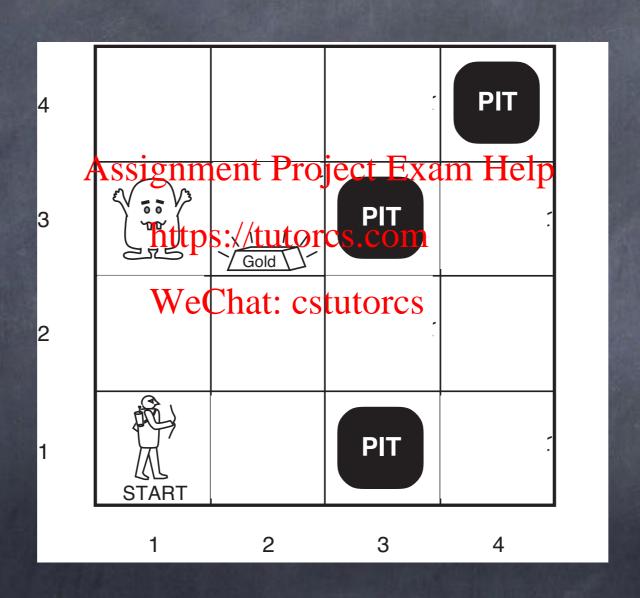
- Impose a structure on the representation of states: Variables, Domains, Constraints
- Backtracking (DFS) search for complete,
 consistent assignment of values to variables
- Inference (constraint propagation) can reduce the domains of variables
 - Preprocessing and/or interleaved with search
- Useful problem-independent heuristics

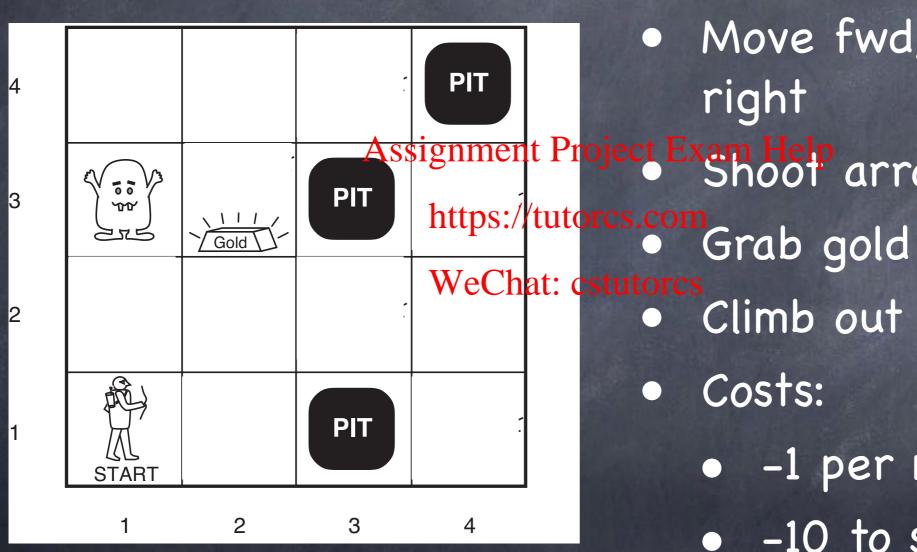
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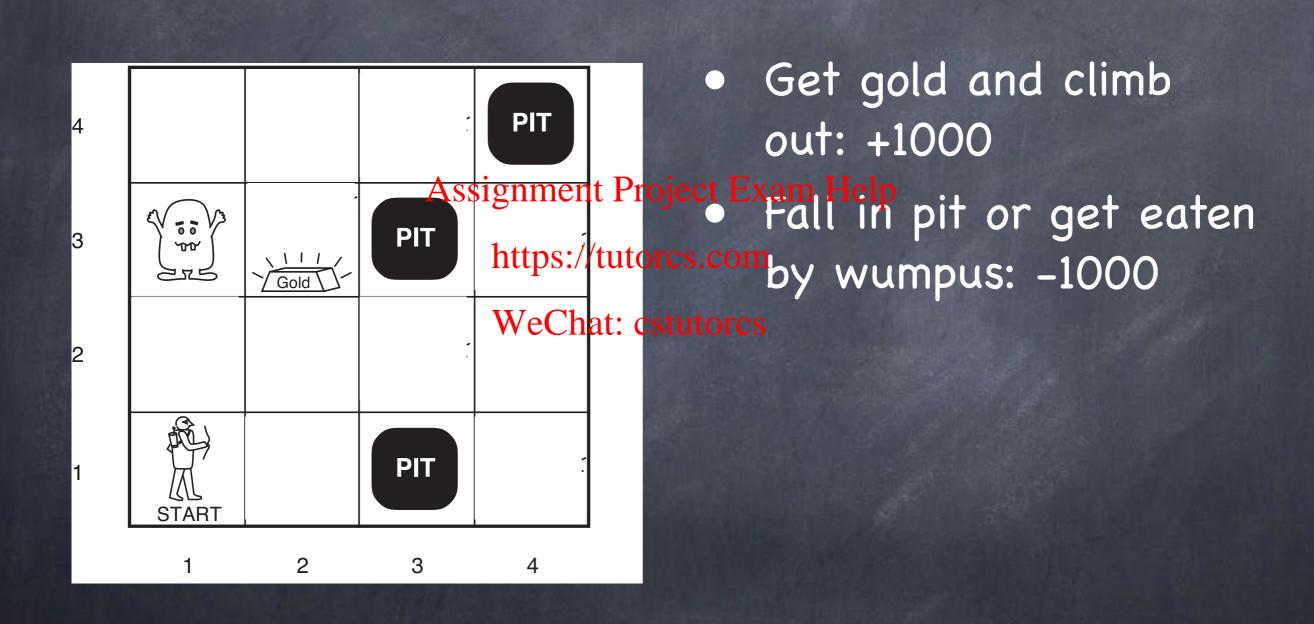


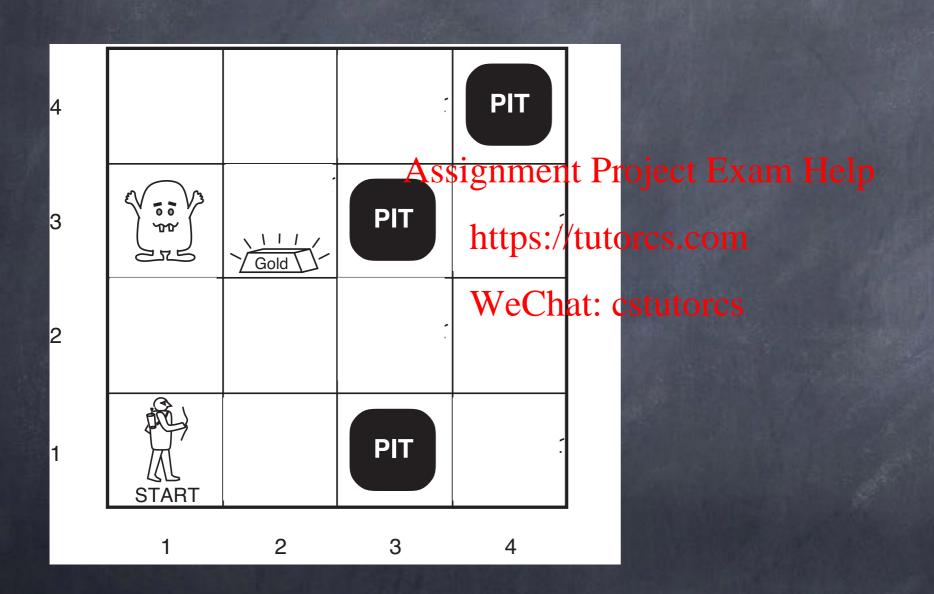


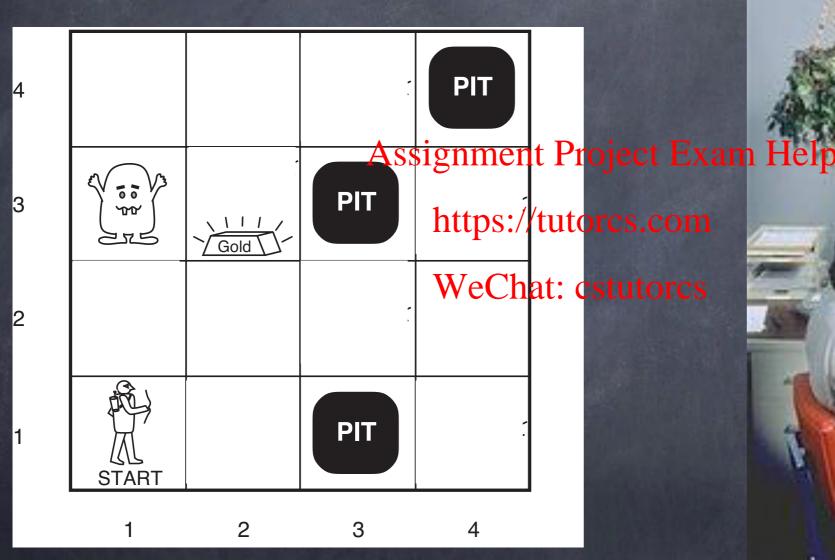




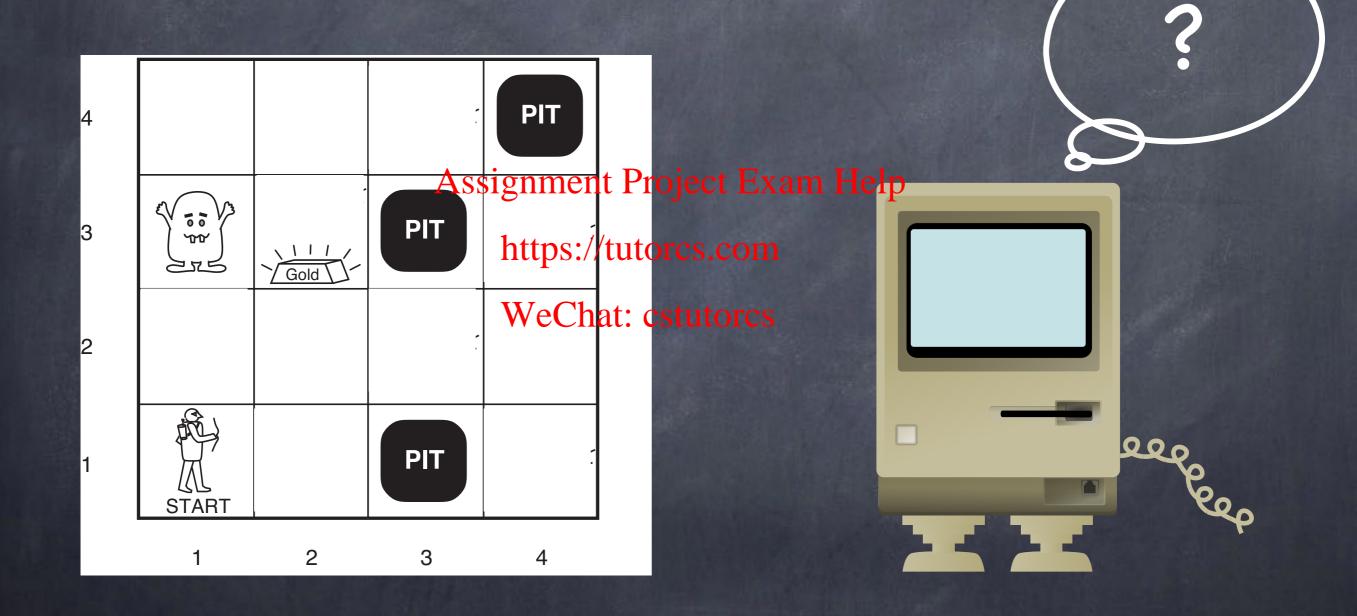
- Move fwd, turn left/ right
- Shoot arrow (once)
 - - Climb out (from [1,1])
 - Costs:
 - -1 per move
 - -10 to shoot









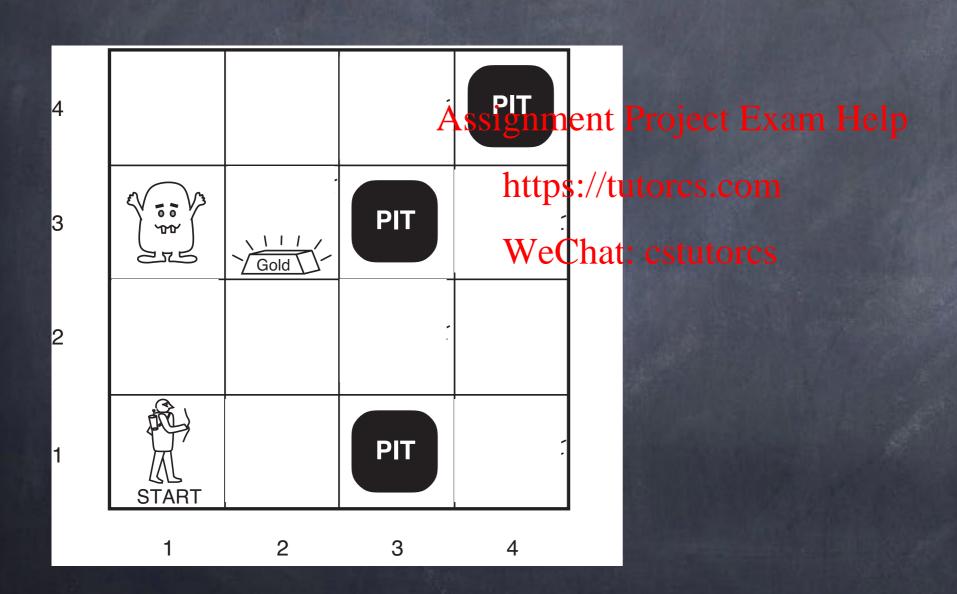


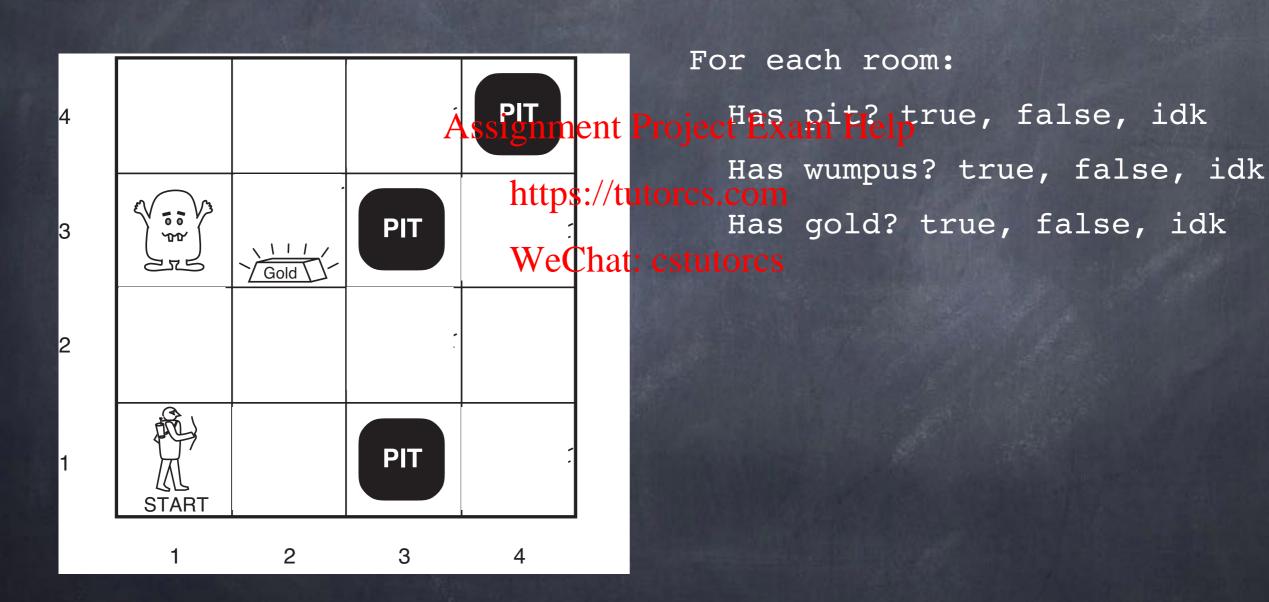
Boolean CSP

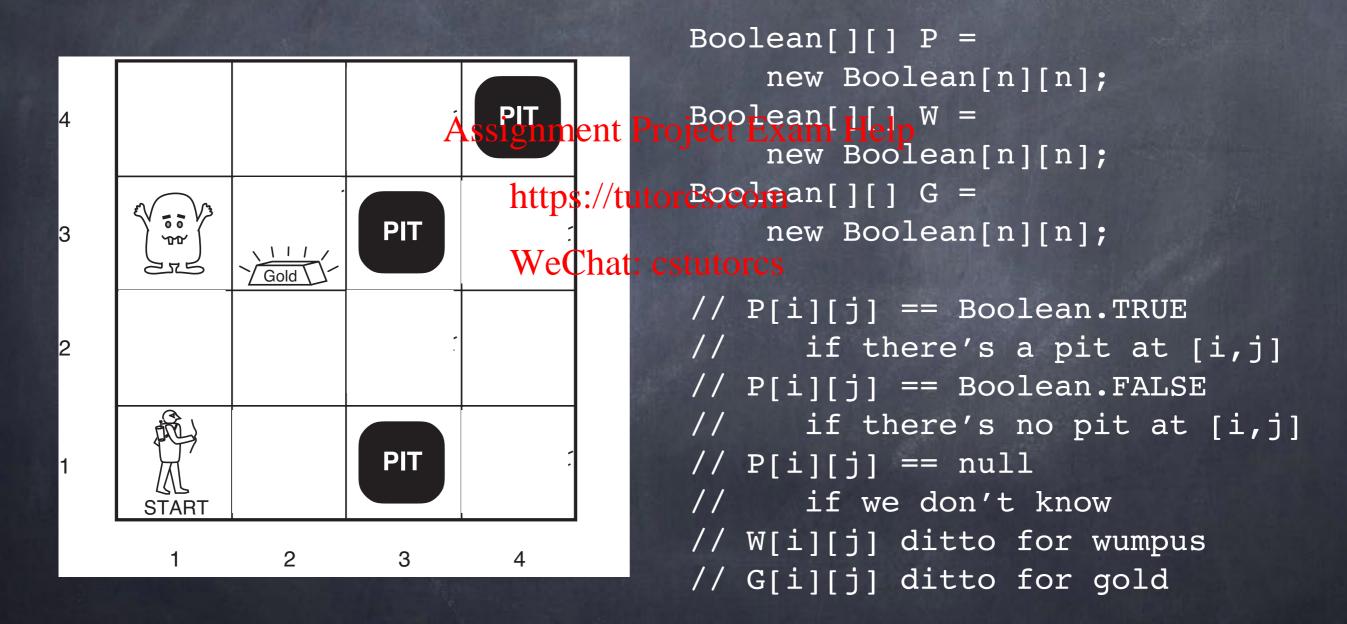
- All variables must be Booleans
 - Domains sall mentringe, tals elep

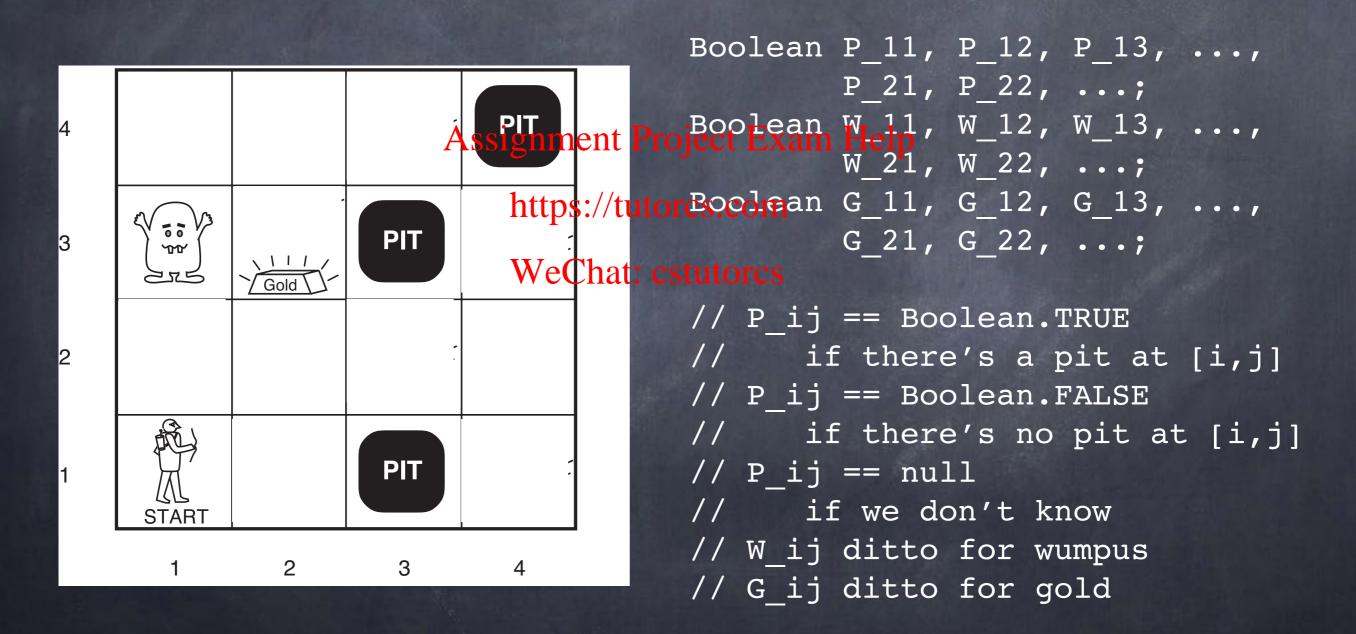
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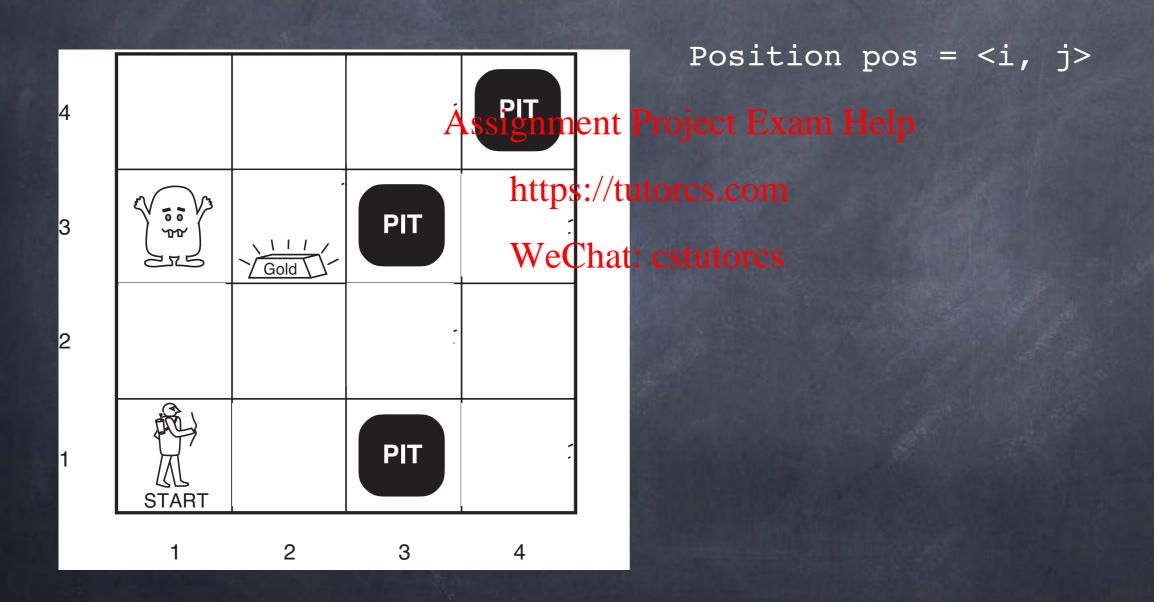
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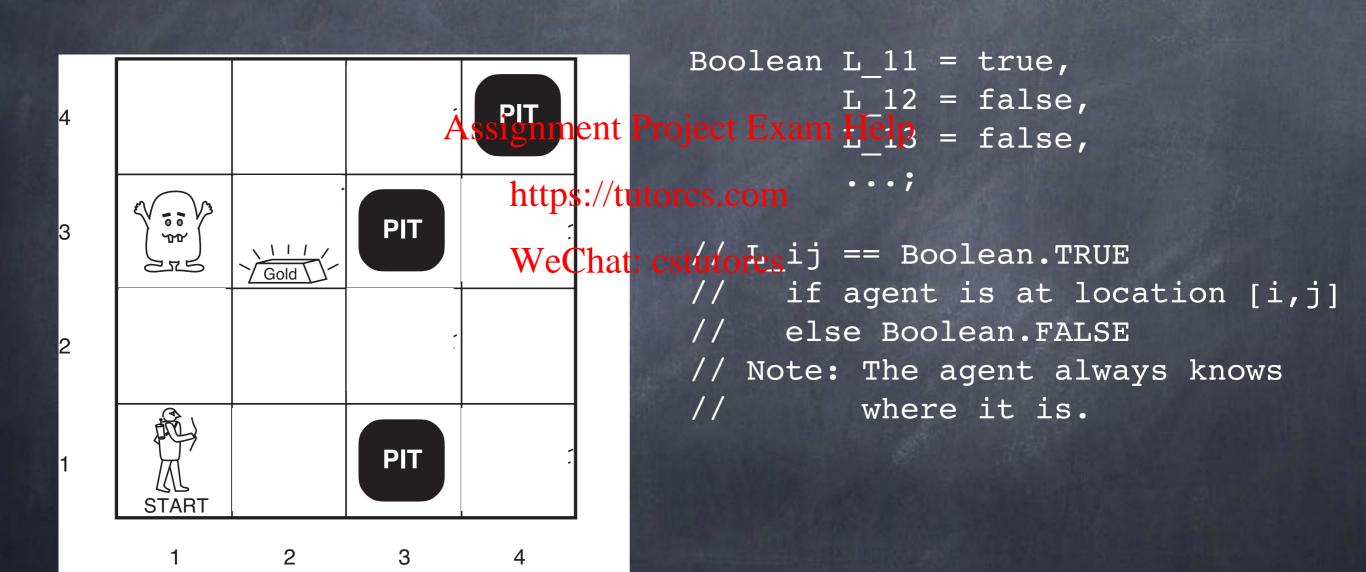


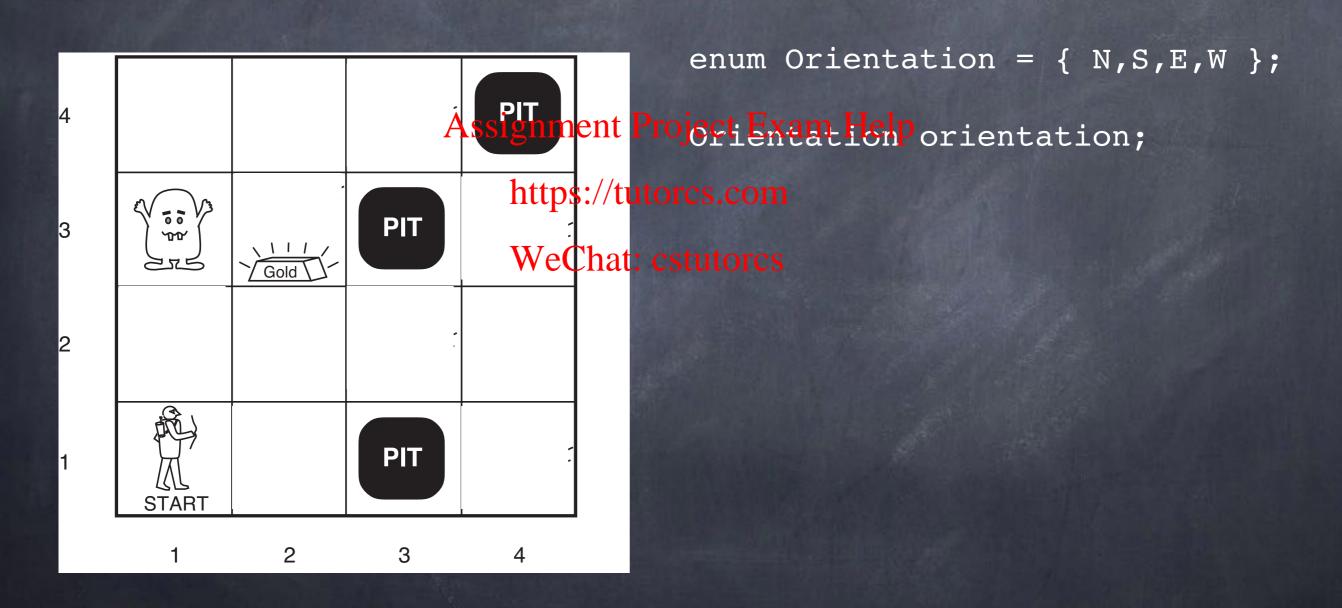


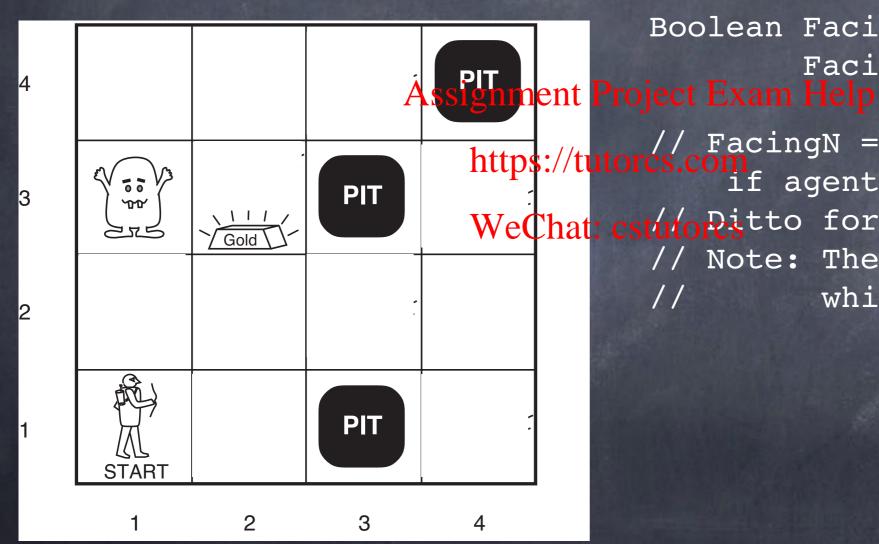




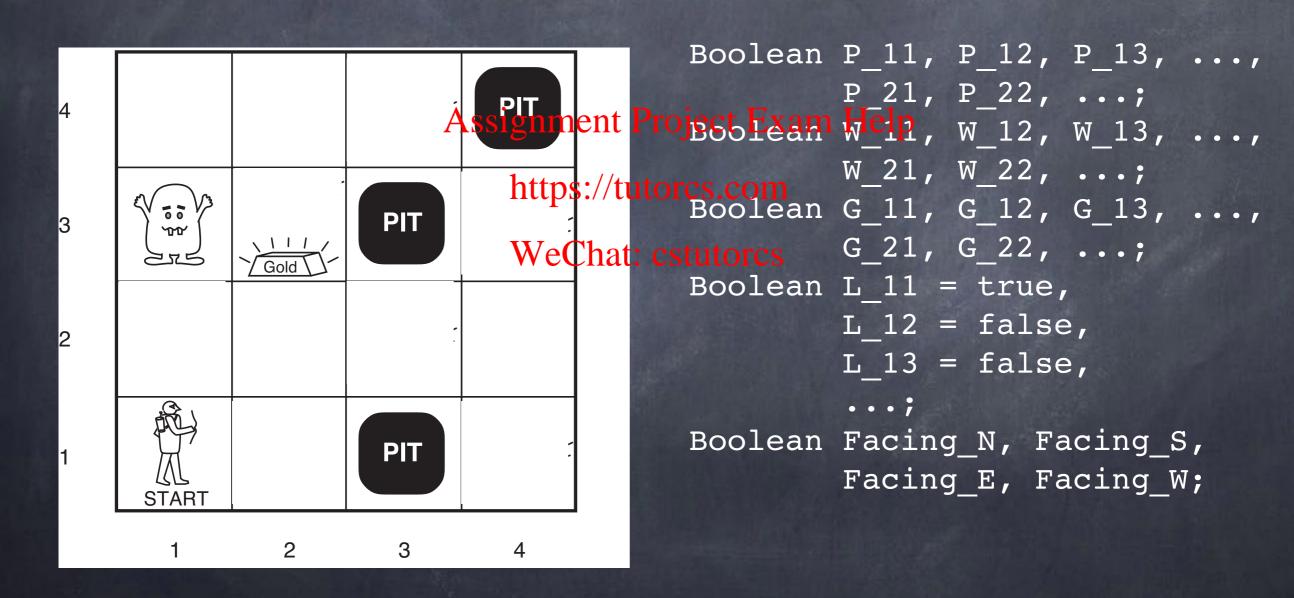


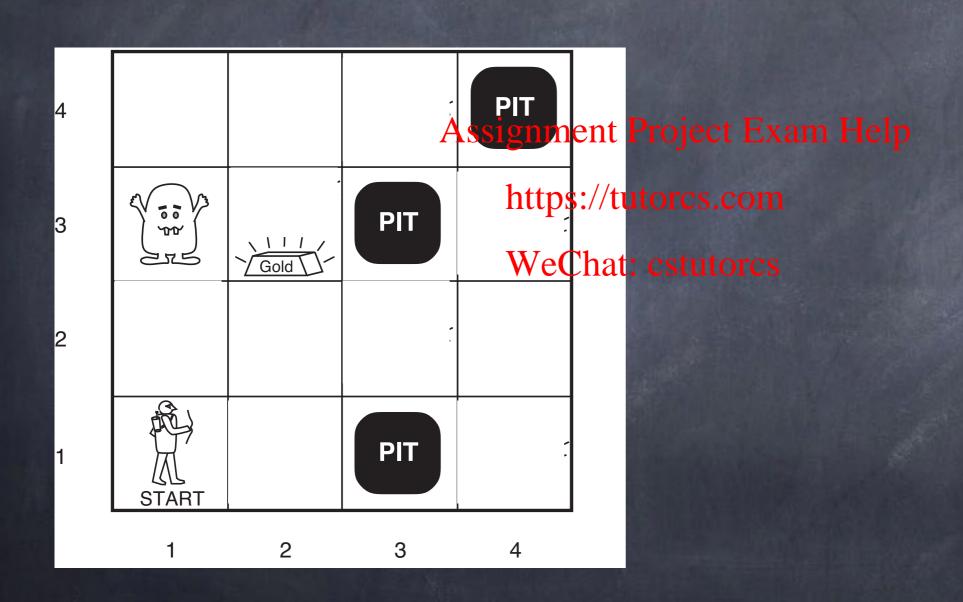




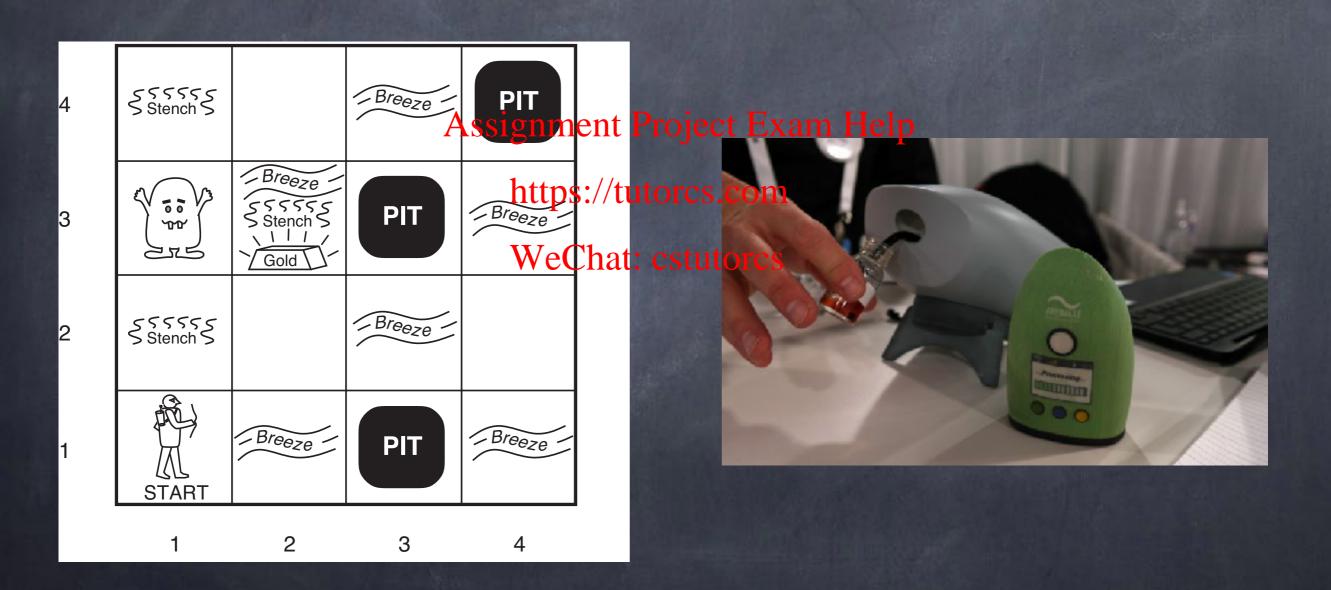


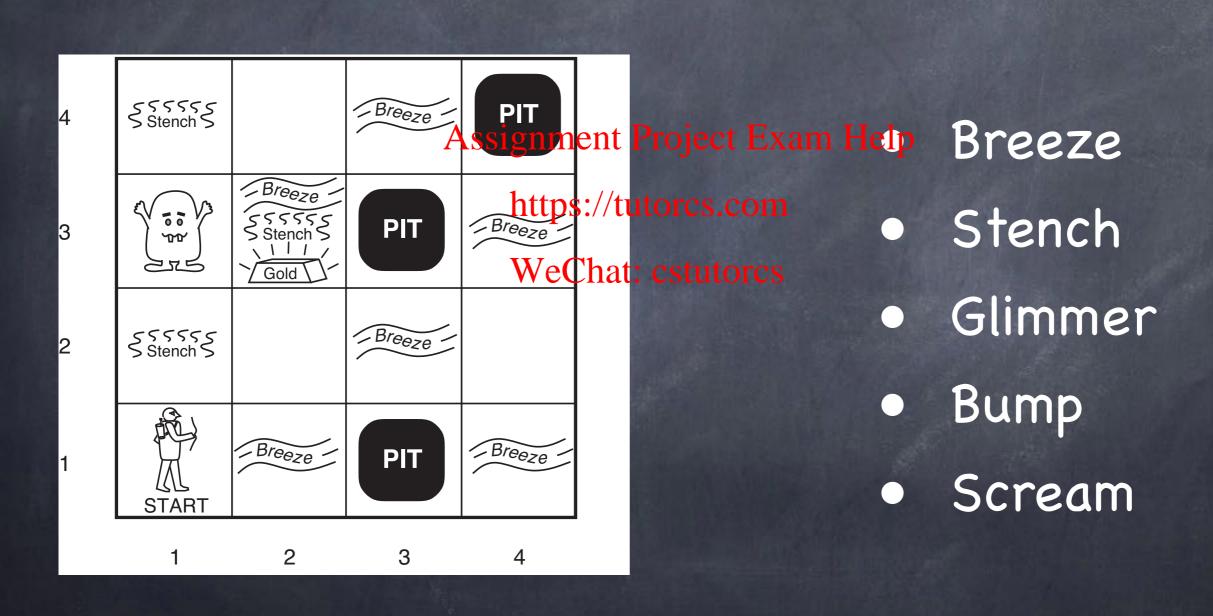
```
Boolean Facing N, Facing S,
                  Facing E, Facing W;
https://tutorcs.com == Boolean.TRUE
              if agent is facing north
We Chat: cstuto Pitto for the other directions
          // Note: The agent always knows
                   which way it is facing
```

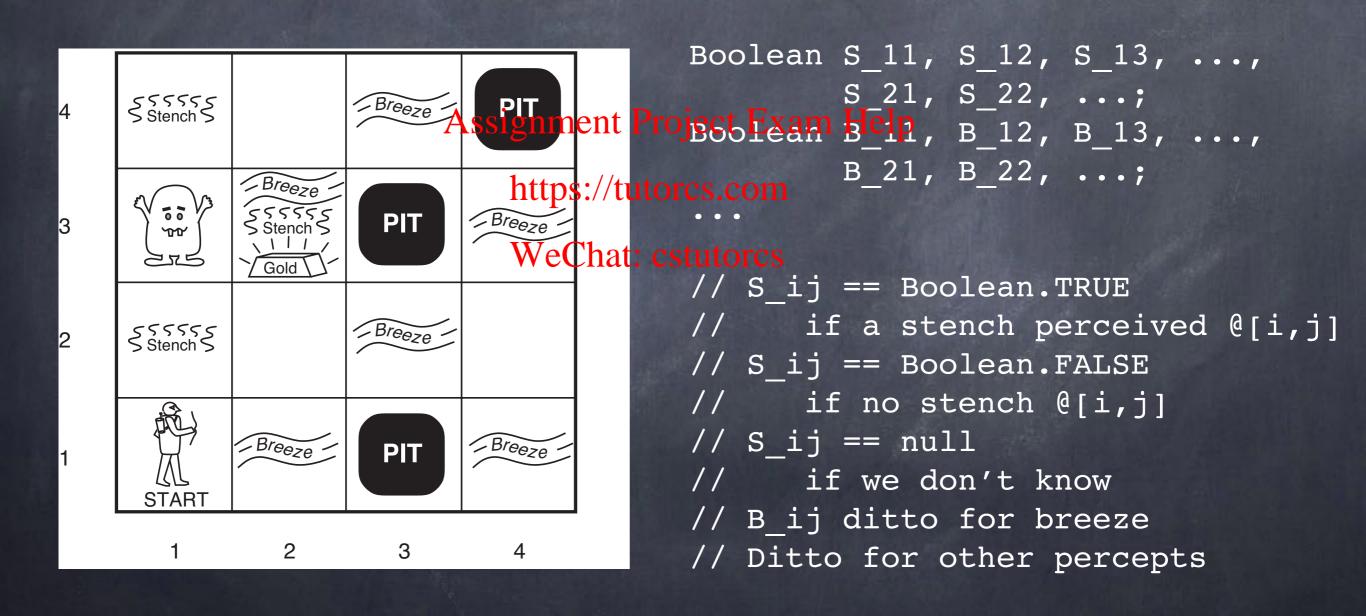


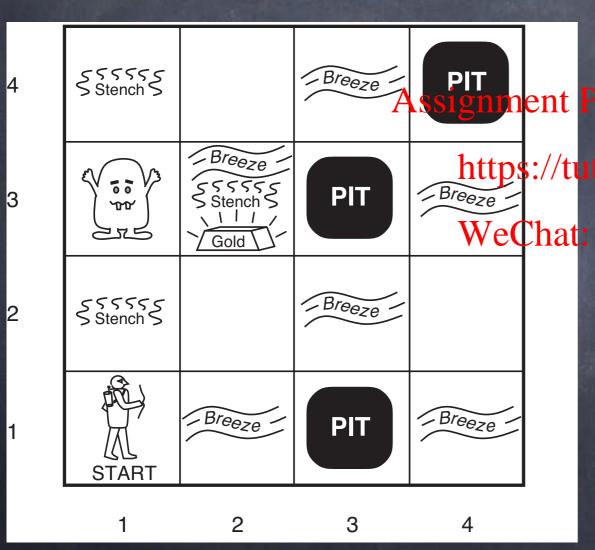












```
Boolean P_11, P_12, P_13, ...,
                  P 21, P 22, ...;
  nent Project Exam Welp, w 12, w 13, ...,
                  W 21, W 22, ...;
https://tutorcs.com
an G_11, G_12, G_13, ...,
WeChat: cstutorcs G_21, G_22, ...;
          Boolean L 11 = true,
                  L 12 = false,
                  L 13 = false,
          Boolean Facing N, Facing S,
                  Facing E, Facing W;
          Boolean S_11, S_12, S_13, ...,
                  S 21, S 22, ...;
          Boolean B 11, B 12, B 13, ...,
                  B_21, B_22, ...;
```

Constraints

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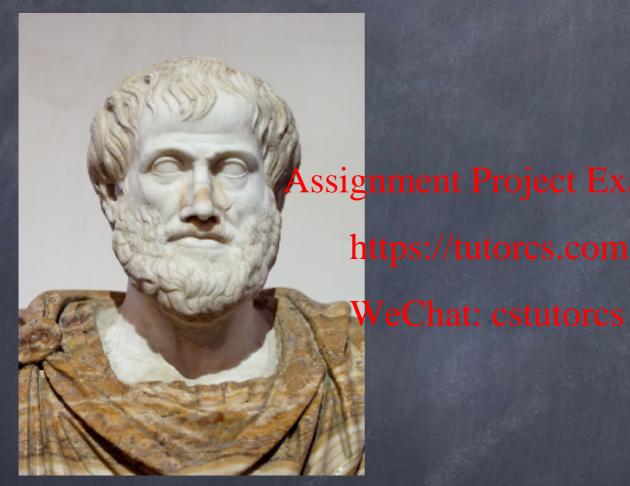
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Constraints

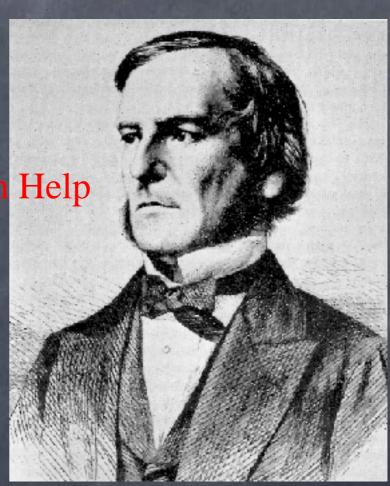
- Constraints are Boolean functions of the variables
 Assignment Project Exam Help
 - $WA \neq NT$ https://tutorcs.com
 - $T_2 \ge T_1 + 10^{\text{WeChat: cstutorcs}}$
 - *AllDiff*(*A*1,*A*2,*A*3,*B*1,*B*2,*B*3,*C*1,*C*2,*C*3)

Constraints

- Constraints are Boolean functions of the variables
 Assignment Project Exam Help
 - $WA \neq NT$ https://tutorcs.com
 - $T_2 \ge T_1 + 10^{\text{hat: cstutorcs}}$
 - *AllDiff*(*A*1,*A*2,*A*3,*B*1,*B*2,*B*3,*C*1,*C*2,*C*3)
- Constraints on Boolean variables are Boolean functions of Boolean values



Assignment Project Exam Help https://tutorcs.com



Aristole (384BC - 332BC)

George Boole (1815-1864)

Propositional Logic (Boolean Algebra)

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A Programming Language for Knowledge!

Propositions

Propositions: things that can be true or false

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Propositions

- Propositions: things that can be true or false
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- Atomic propositions:s.com
 - "It is raining that: cstutores
 - "Socrates was a person"
 - "The wumpus is in room [2,2]"

Connectives (Operators)

- Combine propositions into larger propositions propositions Project Exam Help
 - \bullet \neg , \land , \lor , \Rightarrow https://tutorcs.com

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- \bullet $\neg Raining$
- $Raining \land Cold, Raining \lor Sunny$
- $Raining \land BelowFreezing \Rightarrow Slippery$

Connectives (Operators)

- Combine propositions into larger propositions propositions.

 Project Exam Help
- Syntax

- \neg , \wedge , \vee , \Rightarrow https://tutorcs.com
 - WeChat: cstutorcs
- \bullet $\neg Raining$
- $Raining \land Cold, Raining \lor Sunny$
- $Raining \land BelowFreezing \Rightarrow Slippery$

Connectives (Operators)

• Combine propositions into larger propositions Assignment Project Exam Help

Syntax

 \bullet \neg , \land , \lor , \Rightarrow htt \overrightarrow{ps} .//tutorcs.com

• Each connective represents a Boolean function of its (Boolean) arguments

Semantics

Connectives

| p | $\neg p$ | ot Decided E | vom Holo | |
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| | | | | |
| | | | | |

Connectives

| p | q | $\neg p$ | ALCOHOLD BUILDING | $p \vee q$ | $p \Rightarrow q$ | $p \Leftrightarrow q$ |
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Sentences (Expressions)

• Every sentence of propositional logic represents ("denotes") a Boolean function of its (Boolean) arguments

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Sentences (Expressions)

- Every sentence of propositional logic represents ("denotes") a Boolean function of its (Boolean) arguments
- The meaning of the sentence (the Boolean function that it denotes) is the composition of its parts ("compositional semantics")

 $L_{1,1}$: True if the agent is in room [1,1]

 $W_{1,2}$: True if Athen wurmpeus x is time room [1,2]

 $W_{2,1}$: True if the wumpus is in room [2,1] WeChat: cstutorcs

Possible Worlds

| A CONTRACTOR AND A CONT | AND THE RESERVE OF THE PARTY OF | A ROBERT REPORT OF THE PARTY OF | THE STATE OF |
|--|--|---------------------------------|---------------------|
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A Sentence

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project E | |
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| T | F | T | |
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| T | T | T | |

Meaning of a Sentence

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$ |
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| T | T | F | T | Time |
| T | T | T | T | T |

Meaning of a Sentence



| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project F | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1}$ $(W_{1,2} \lor W_{2,1})$ |
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| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$ |
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| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project H | $W_{1,2} ee W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$ |
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| $L_{1,1}$ | $W_{1,2}$ Assis | $W_{2,1}$ $\mathbf{gnment\ Project\ F}$ | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \lor W_{2,1})$ |
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| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project F | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \lor W_{2,1})$ |
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| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project F | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1}$ $(W_{1,2} \lor W_{2,1})$ |
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Propositional Logic and Boolean CSPs

- Every sentence of propositional logic represents ("denotes") a Boolean function of its (Boolean) arguments
- Constraints on Boolean values
 Boolean functions of Boolean values

Satisfiability

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project F | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$ |
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| T | T | T | T | T |

Inconsistency

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ | $W_{1,2} {ee} W_{2,1}$ Exam Help | $L_{1,1} \wedge (W_{1,2} \lor W_{2,1})$ |
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| T | T | T | T | T |

Inconsistency

 $L_{1,1} \wedge (W_{1,2} \lor W_{2,1})$

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ | $W_{1,2} \lor W_{2,1}$ | $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$ |
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Models

 $L_{1,1} \wedge (W_{1,2} \vee W_{2,1})$

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ gnment Project F | $W_{1,2} \lor W_{2,1}$ Exam Help | $L_{1,1} \land (W_{1,2} \lor W_{2,1})$ |
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Models

 $\{L_{1,1}, (W_{1,2} \lor W_{2,1})\}$

| $L_{1,1}$ | $W_{1,2}$ | $W_{2,1}$ | $W_{1,2} \lor W_{2,1}$ Exam Help | $\{L_{1,1}, (W_{1,2} \lor W_{2,1})\}$ |
|-----------|-----------|--------------------|-------------------------------------|---------------------------------------|
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Unsatisfiable

 $L_{1,1} \wedge W_{1,2} \wedge \neg W_{1,2}$

| $L_{1,1}$ | $W_{1,2}$ | $L_{1,1} \wedge W_{1,2}$ gnment Project F | $ eg W_{1,2}$ | $L_{1,1} \wedge W_{1,2} \wedge $ $\neg W_{1,2}$ |
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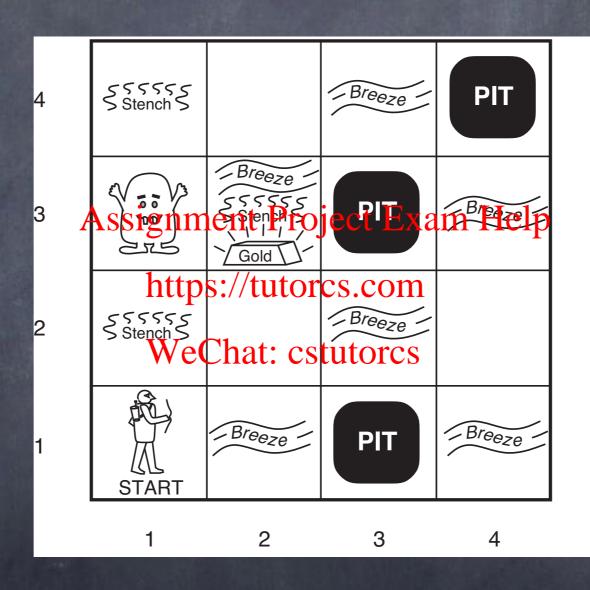
Unsatisfiable

 $\{L_{1,1}, W_{1,2}, \neg W_{1,2}\}$

| $L_{1,1}$ | $W_{1,2}$ Assignn | $ eg W_{1,2}$ nent Project Exam | $\{\; L_{1,1}, W_{1,2}, eg W_{1,2} \; \}$ |
|-----------|-------------------|---------------------------------|---|
| F | F http | s://tutorcs.com | F |
| F | T We | Chat: estutores | F |
| T | F | T | F |
| T | T | F | F |

Propositional Logic and Boolean CSPs

- Every sentence of propositional logic represents a Boolean function of its Assignment Project Exam Help atomic propositions https://tutorcs.com
- Each assignment of strue or false to the atomic propositions is one possible world
- That world is consistent with the sentence if the function denoted by the sentence is true given that assignment



 $P_{1,1}, P_{1,2}, \dots$: There is a pit at [1,1], [1,2], ... $W_{1,1}, W_{1,2}, \dots$: The wumpus is at [1,1], [1,2], ...

•••

 $B_{1,1}, B_{1,2}, \ldots$: Yösisperteived an breeze at [1,1], ...

 $S_{1,1}, S_{1,2}, \ldots$: You perceived a stench at [1,1], ...

•••

 $L_{1,1}, L_{1,2}, \dots$: The agent is at [1,1], ...

Facingn, Facings, Facinge, Facingw

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• You perceive a breeze in a room if that room is adjacent to a room that contains a pittps://tutorcs.com

 You perceive a breeze in a room only if that room is adjacent to a room that Assignment Project Exam Help contains a pit ttps://tutorcs.com

- You perceive a breeze in a room if and only if that room is adjacent to a room that contains a pit
- · Rooms adjace chatospits are breezy.

- You perceive a breeze in a room if and only if that room is adjacent to a room that contains a pit
- Rooms adjace chatospits have breezes.

 $B_{i,j} \Leftrightarrow P_{k,l}$ for some room [k,l] adjacent to [i,j]

- You perceive a breeze in a room if and only if that room is adjacent to a room that contains a pit
- Rooms adjace chatospits have breezes.

 $B_{i,j} \Leftrightarrow P_{k,l}$ for some room [k,l] adjacent to [i,j]

- You perceive a breeze in a room if and only if that room is adjacent to a room that contains a pit
- Rooms adjace chatospits have breezes.

 $B_{i,j} \Leftrightarrow P_{k,l}$ for some room [k,l] adjacent to [i,j]

- You perceive a breeze in a room if and only if that room is adjacent to a room that contains a pit
- · Rooms adjace chatospits have breezes.
- You perceive a breeze in [1,1] iff there is a pit in [1,2] or [2,1]

$$B_{1,1} \Leftrightarrow P_{1,2} \vee P_{2,1}$$

- You perceive a breeze in a room if and only if that room is adjacent to a room Assignment Project Exam Help that contains a pit https://tutorcs.com
- Rooms adjacent to pits have breezes.
- You perceive a breeze in [1,1] iff there is a pit in [1,2] or [2,1]
- You perceive a breeze in [1,2] iff there is a pit in [1,1] or [2,2] or [3,1]

$$B_{1,2} \Leftrightarrow P_{1,1} \vee P_{2,2} \vee P_{3,1}$$

$$B_{1,1} \Leftrightarrow P_{1,2} \vee P_{2,1}$$
 $B_{1,2} \Leftrightarrow P_{1,1} \vee P_{2,2} \vee P_{3,1}$
Assignment Project Exam Help
 $B_{2,2} \Leftrightarrow P_{1,2} \vee P_{2,3} \vee P_{3,2} \vee P_{2,1}$

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• • •

$$B_{1,1} \Leftrightarrow P_{1,2} \vee P_{2,1}$$
 $B_{1,2} \Leftrightarrow P_{1,1} \vee P_{2,2} \vee P_{3,1}$
Assignment Project Exam Help
 $B_{2,2} \Leftrightarrow P_{1,2} \vee P_{2,2} \vee P_{3,2}$
 $P_{2,1}$

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•••

$$S_{1,1} \Leftrightarrow W_{1,2} \vee W_{2,1}$$

 $S_{1,2} \Leftrightarrow W_{1,1} \vee W_{2,2} \vee W_{3,1}$
 $S_{2,2} \Leftrightarrow W_{1,2} \vee W_{2,3} \vee W_{3,2} \vee W_{2,1}$

• • •

• A room is safe ("OK") if and only if it does not contain either a pit or the wumpus

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• A room is safe ("OK") if and only if it does not contain either a pit or the wumpus

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$$OK_{1, W}$$
ethat: C ellores V $W_{1,1})$

$$OK_{1,2} \Leftrightarrow \neg (P_{1,2} \lor W_{1,2})$$

$$OK_{2,1} \Leftrightarrow \neg(P_{2,1} \lor W_{2,1})$$

• • •

- There is exactly one wumpus.
- The wumpusgiseinpexactly tope room.

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- There is exactly one wumpus.
- The wumpusgiseinpexactly tope room.
- There is a wumpusting at least one of the rooms AND at wumpus cannot be in two rooms.

- There is exactly one wumpus.
- The wumpusgiseinpexactly tope room.
- There is a wumpusting at least one of the rooms AND at wumpus cannot be in two rooms.

$$W_{1,1} \vee W_{1,2} \vee ... \vee W_{3,4} \vee W_{4,4}$$

 $\neg (W_{1,1} \wedge W_{1,2}), \neg (W_{1,1} \wedge W_{1,3}), ..., \neg (W_{3,4} \wedge W_{4,4})$

$$B_{1,1} \Leftrightarrow P_{1,2} \vee P_{2,1}$$

$$B_{1,2} \Leftrightarrow P_{1,1} \vee P_{2,2} \vee P_{3,1}$$

$$B_{2,2} \Leftrightarrow P_{1,2} \vee P_{2,3} \text{ in } P_{3,2} \text{ is } OK_{1,1} \Leftrightarrow \neg (P_{1,1} \vee W_{1,1})$$

$$\dots \qquad \qquad \text{https://tutores.com } OK_{1,2} \Leftrightarrow \neg (P_{1,2} \vee W_{1,2})$$

$$S_{1,1} \Leftrightarrow W_{1,2} \vee W_{2,1} \text{ we Chat: estutores } OK_{2,1} \Leftrightarrow \neg (P_{2,1} \vee W_{2,1})$$

$$S_{1,2} \Leftrightarrow W_{1,1} \vee W_{2,2} \vee W_{3,1} \qquad \dots$$

$$S_{2,2} \Leftrightarrow W_{1,2} \vee W_{2,3} \vee W_{3,2} \vee W_{2,1}$$

$$\dots$$

 $W_{1,1} \lor W_{1,2} \lor ... \lor W_{3,4} \lor W_{4,4}$ $\neg (W_{1,1} \land W_{1,2}), \neg (W_{1,1} \land W_{1,3}), ..., \neg (W_{3,4} \land W_{4,4})$

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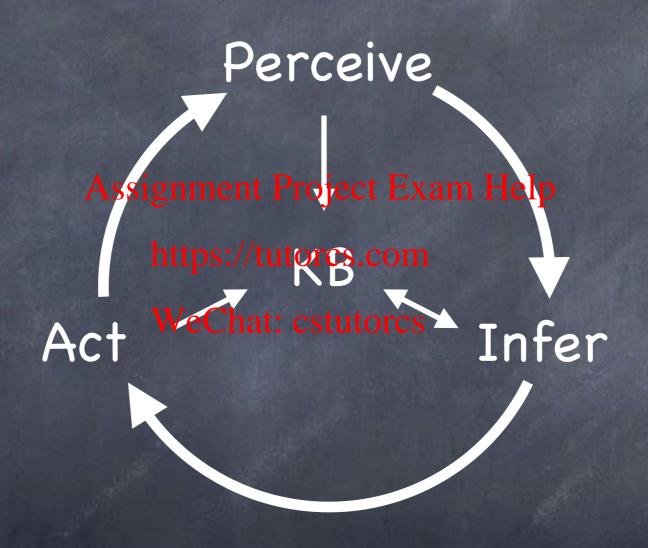
 Maintain a knowledge base (KB) of sentences believed to be true Assignment Project Exam Help

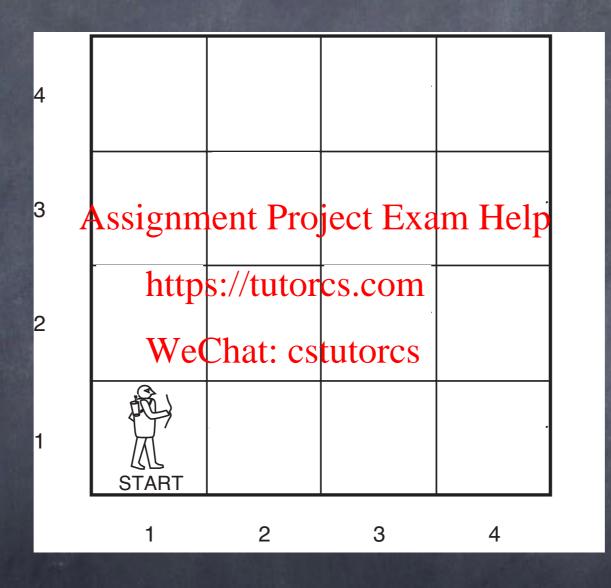
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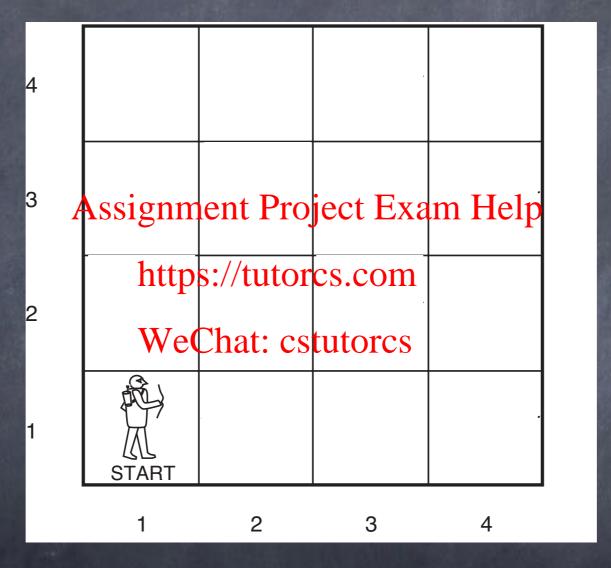
- Maintain a knowledge base (KB) of sentences believed to be true Assignment Project Exam Help
- Perceives the worlds (and updates its beliefs)
 WeChat: cstutores

- Maintain a knowledge base (KB) of sentences believed to be true Assignment Project Exam Help
- Perceives the worlds (and updates its beliefs)
 WeChat: cstutorcs
- Infers what to do next

- Maintain a knowledge base (KB) of sentences believed to be true Assignment Project Exam Help
- Perceives the worlds (and updates its beliefs)
 WeChat: cstutores
- Infers what to do next
- Performs an action (and updates its beliefs)

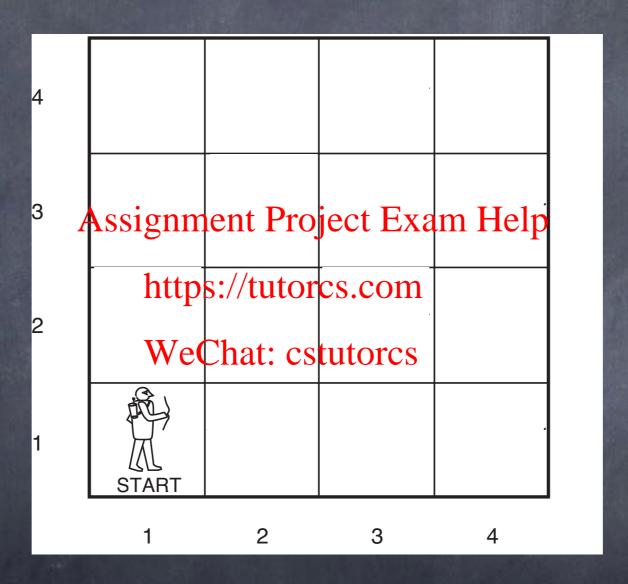






 $L_{1,1}, \neg L_{1,2}, ... \neg L_{3,4}, \neg L_{4,4}$ $FacingE, \neg FacingN, \neg FacingS, \neg FacingW$ $OK_{1,1}$

Perception



$$\neg B_{1,1}, \ \neg S_{1,1}$$

Inference

- Given what I know...
 - What shoulded pagest Exam Helpee AIMA 7.7

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Inference

- Given what I know...
 - What shoulded page Exam Help
 - Is room [2,1]:/orto[1,2] safe?

- Given what I know...
 - What shoulded paget Exam Help
 - Is room [2,1]:/orto[1,2] safe?
 - Is room [2,1] safe?

- Given what I know...
 - What shoulded pagest Exam Help
 - Is room [2,11]://https://htt
 - Is room [2,1] safe?
 - Is there no pit in room [2,1]?

Given what I know... Is there no pit in room [2,1]?

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KB

 $\neg P_{2,1}$?

Given what I know... Is there no pit in room [2,1]?

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 R_1 : $\neg P_{1,1}$

 R_2 : $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$ WeChat: cstutorcs $\neg P_{2,1}$?

 $\neg B_{1,1}$

Possible Worlds

| $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $B_{1,1}$ | | | |
|-----------|-----------|-----------|---------------------------|-----------|------|--|
| F | F | Āssig | nment Pro | ject Exam | Help | |
| F | F | F h | ttps://tutor | cs.com | | |
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| ••• | | | | | | |
| Т | Т | F | T | | | |
| T | T | T | F | | | |
| T | T | T | T | | | |

Knowledge

| $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $B_{1,1}$ | R_1 | R_2 | $\neg B_{1,1}$ | $\neg P_{2,1}$ |
|-----------|-----------|-----------|--------------|-----------|-------|----------------|----------------|
| F | F | Assig | nment Pro | ject Exam | Help | T | |
| F | F | F h | ttps://tutor | cs.com | F | F | |
| F | F | T V | VeChat: cs | tutorcs | F | Т | |
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| Т | Т | F | Т | F | T | F | |
| Т | Т | T | F | F | F | Т | |
| T | T | J | T | F | T | F | |

Inconsistent Worlds

Knowledge

| $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $B_{1,1}$ | R_1 | R_2 | $\neg B_{1,1}$ | $\neg P_{2,1}$ |
|-----------|-----------|------------------|---------------------------|-----------|-------|----------------|--------------------|
| F | F | Assig | nment Pro | ject Exam | Help | T | |
| | | - F h | ttps://tutor | cs.com | Г | F | |
| | | TV | VeCl <mark>pat: cs</mark> | tutores | F | - | |
| ••• | | | | ••• | | | |
| Ţ | T | F | T | F | T | F | |
| T | T | T | F | | F | T | |
| T | T | T | T | F | T | F | THE REAL PROPERTY. |

Models

Knowledge

| $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $B_{1,1}$ | R_1 | R_2 | $\neg B_{1,1}$ | $\neg P_{2,1}$ |
|-----------|-----------|------------------|--------------|-----------|-------|----------------|----------------|
| F | F | Assig | nment Pro | ject Exam | Help | T | |
| F | F | - F h | ttps://tutor | cs.com | F | F | |
| F | F | T | VeChat: cs | tutorcs | F | T | |
| ••• | | | | ••• | | | |
| T | T | F | T | F | T | F | |
| T | T | T | F | F | F | T | |
| T | Т | T | T | F | Т | F | |

Query

| | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $B_{1,1}$ | R_1 | R_2 | $\neg B_{1,1}$ | $\neg P_{2,1}$ |
|------|-----------|-----------|----------------|---------------------------|-----------|-------|----------------|----------------|
| | F | F | Assig | nment Pro | ject Exam | Help | Т | T |
| | F | F | F h | ttps://tutor | cs.com | F | F | |
| | F | F | T | VeCl <mark>rat: cs</mark> | tutorcs | F | T | |
| | ••• | | | | ••• | | | |
| Hess | T | T | F | T | F | T | F | |
| | T | T | T | F | F | F | T | |
| | T | Т | T | T | F | Т | F | |

- α entails β : $\alpha \models \beta$
 - Every model of β

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- α entails β : $\alpha \models \beta$
 - Every madelneft rajist elsa Helpmodel of β
 - Whenever α is true, so is β
 - β is true in every world consistent with α
 - $Models(\alpha) \subseteq Models(\beta)$
 - β logically follows from α

- Is very conservative
 - Only accepts a gonelusion that is guaranteed to be true whenever the premises are atrue orcs

- Is very conservative
 - Only accepts a gonelusion that is guaranteed ptombes true whenever the premises are at rue orcs
- If β is false in every model of α , then $\alpha \vDash \neg \beta$

- Is very conservative
 - Only accepts a conclusion that is guaranteed to be true whenever the premises are at rue or s
- If β is false in every model of α , then $\alpha \models \neg \beta$
- Otherwise: don't know!

Given what I know... Is there no pit in room [2,1]?

 $R_1: \neg P_{1,1}$

 R_2 : $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_{2,1})$ WeChat: cstutorcs $\neg P_{2,1}$?

 $\neg B_{1,1}$

 $KB \vDash \neg P_{2,1}$

Given what I know... Is there no pit in room [1,2]?

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 $\neg P_{1,2}$?

$$R_1$$
: $\neg P_{1,1}$ https://tutorcs.com

$$R_2$$
: $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_2 G)$ at: cstutorcs

$$R_3: B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$$

$$\neg B_{1,1}$$

$$B_{2,1}$$

| $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|-----------|-----------|-----------|-----------|----------------|---------------|-------------|-------------|-------------|-------|-------|-------|----|
| F | F | F | F | F | F | F | T | T | T | T | F | F |
| F | F | F | F | F Assign | F ment | T Projec | T t Exan | T n Help | F | T | F | F |
| : | • | | | ht | : tps://tu | itores. | com | | | • | • | |
| F | T | F | F | F _W | F eChat | F | orcs | Т | F | T | T | F |
| F | T | F | F | F | F | T | T | T | T | T | T | Т |
| F | T | F | F | F | T | F | T | T | Т | T | T | T |
| F | T | F | F | F | T | Т | T | T | T | T | T | Т |
| F | T | F | F | T | F | F | T | F | F | T | T | F |
| : | | : | : | | | : | | : | | : | | : |
| Т | T | T | T | T | T | T | F | T | T | F | T | F |

Possible Worlds Inference

| $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | \overline{KB} |
|-----------|-----------|-----------|-----------|------------------|---------------|-------------|-------------|-------------|-------|-------|-------|-----------------|
| F | F | F | F | F | F | F | T | T | T | Т | F | F |
| F | F | F | F | F Assign | F ment | T Projec | T t Exan | T 1 Help | F | T | F | F |
| : | : | : | | : ht | : tps://tu | tores. | com | | • | • | • | |
| F | T | F | F | $F_{\mathbf{W}}$ | F eChat | F | orcs | Т | F | T | T | F |
| F | T | F | F | F | F | T | T | T | T | T | T | T |
| F | T | F | F | F | T | F | T | T | T | T | T | T |
| F | T | F | F | F | Т | Т | T | T | T | T | T | T |
| F | Т | F | F | T | F | F | T | F | F | T | T | F |
| : | | : | : | : | | : | : | : | | | | |
| Т | T | T | T | T | T | T | F | T | T | F | T | F |

Inference_{Knowledge}

| $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|-----------|-----------|-----------|-----------|----------------|---------------|-------------|-------------|-------------|-------|-------|-------|----|
| F | F | F | F | F | F | F | T | T | T | T | F | F |
| F | F | F | F | F Assign | F ment | T Projec | T t Exan | T n Help | F | T | F | F |
| : | • | | | ht | : tps://tu | itores. | com | | | • | • | |
| F | T | F | F | F _W | F eChat | F | orcs | Т | F | T | T | F |
| F | T | F | F | F | F | T | T | T | T | T | T | Т |
| F | T | F | F | F | T | F | T | T | Т | T | T | T |
| F | T | F | F | F | T | Т | T | T | T | T | T | Т |
| F | T | F | F | T | F | F | T | F | F | T | T | F |
| : | : | : | : | | | : | | : | | : | | : |
| Т | T | T | T | T | T | T | F | T | T | F | T | F |

Impossible Worlds

| $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|-----------|-----------|-----------|-----------|-----------|------------|-----------|-----------|-------------|-------|--------------|-------|------|
| F | F | F | F | F | F | F | T | T | T | T | F | F |
| F | Г | Г | Г | A seign | ment | Projec | – Fyan | – 1 Heln | Г | Ŧ | Г | Г |
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| F | Ŧ | Г | Г | | ips://u | TOPES. | COIII — | T | F | T | T | F |
| F | Т | F | F | F | ecnar F | T CStute | T | Т | T | Т | T | Т |
| F | Т | F | F | F | Т | F | Т | Т | Т | T | Т | Т |
| F | Т | F | F | F | Т | Т | Т | Т | Т | T | Т | Т |
| _ | _ | | | _ | | | _ | | | | _ | _ |
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| — | | | | | | | | - | - | | | |
| | | | | | | 12 | | | | Mark Control | 12.6 | |

Models

| $\overline{B_{1,1}}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|----------------------|-----------|-----------|-----------|-----------|-----------|-----------|-------------|--------|-------|-------|-------|----|
| F | F | F | F | F | F | F | T | T | T | T | F | F |
| F | F | F | F | Assion | ment | Projec | T t Exan | n Heln | F | T | F | F |
| • | : | : | | : ht | tns://ti | itores | com | : | • | • | • | |
| F | T | F | F | Fw | eChat | CSTUI | orcs | T | F | T | T | F |
| F | T | F | F | F | F | T | T | T | T | T | T | T |
| F | Т | F | F | F | Т | F | T | T | T | T | T | T |
| F | Т | F | F | F | T | Т | T | T | T | T | T | Т |
| F | Т | F | F | T | F | F | Т | F | F | T | T | F |
| | : | | | | | | | | | | | |
| T | T | T | T | T | T | T | F | T | T | F | T | F |

$$KB \vDash \neg P_{1,2}$$

| | $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $ P_{1,2} $ | $P_{2,1}$ | $ P_{2,2} $ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|---|-----------|-----------|-----------|-------------|-----------|-------------|-----------|--------|--------|-------|-------|-------|----|
| | F | F | F | F | F | F | F | T | T | T | T | F | F |
| | F | F | F | F | Assign | ment | Projec | t Exan | n Heln | F | T | F | F |
| | : | : | : | | : ht | tns://tr | torcs | com | : | : | : | • | |
| | F | T | F | F | FW | eChat | CSTUI | orcs | T | F | T | T | F |
| | F | Т | F | F | F | F | T | T | T | T | T | T | T |
| | F | Т | F | F | F | Т | F | T | T | T | T | T | Т |
| | F | Т | F | F | F | T | Т | T | T | T | T | T | Т |
| 0 | F | Т | F | F | Т | F | F | Т | F | F | T | T | F |
| | | | | | | | | | | | | | |
| | T | T | T | T | T | T | T | F | T | T | F | T | F |

$KB \not\models P_{2,2}$

Inference

 $KB \not\models \neg P_{2,2}$

| $B_{1,1}$ | $B_{1,2}$ | $P_{1,1}$ | $P_{1,2}$ | $P_{2,1}$ | $P_{2,2}$ | $P_{3,1}$ | R_1 | R_2 | R_3 | R_4 | R_5 | KB |
|-----------|-----------|-----------|-----------|--------------|-----------|-----------|-----------|-----------|-------|-------|-------|----|
| F | F | F | F | F | F | F | Т | Т | T | T | F | F |
| F | F | F | F | Assign | ment | Projec | T Fyan | – Heln | F | T | F | F |
| | : | : | : | Assign ht | tng://tn | tores | | : | : | : | • | : |
| F | T | F | F | F | ips.//u | F cotut | | T | F | T | Т | F |
| F | T | F | F | F | F | T | T | T | Ţ | T | T | Т |
| F | Т | F | F | F | T | F | Т | T | T | T | Т | Т |
| F | Т | F | F | F | Т | Т | Т | T | T | T | Т | Т |
| F | Ŧ | F | F | _ | F | F | | F | F | | Ŧ | F |
| : | : | : | • 1 | | | • | | | | | • | |
| Т | Т | T | T | T | T | Т | F | T | Т | F | Т | F |

Given what I know...

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$$R_1$$
: $\neg P_{1,1}$ https://tutorcs.com

$$R_2$$
: $B_{1,1} \Leftrightarrow (P_{1,2} \vee P_2 G)$ at: estutores

$$R_3: B_{2,1} \Leftrightarrow (P_{1,1} \vee P_{2,2} \vee P_{3,1})$$

$$\neg B_{1,1}$$

$$B_{2,1}$$

$$\neg P_{1,2}$$
?

$$KB \vDash \neg P_{1,2}$$

$$KB \not\models P_{2,2}$$

$$KB \not\models \neg P_{2,2}$$

- α entails β : $\alpha \models \beta$
 - Every madelneft rajist elsa Helpmodel of β
 - Whenever α is true, so is β
 - β is true in every world consistent with α
 - $Models(\alpha) \subseteq Models(\beta)$
 - β logically follows from α

Computing Entailment

- \bullet Given knowledge α and query β
 - For everyignossibolectwonldelpu
 - If α is satisfied by w WeChat: cstutores
 - ullet If eta is not satisfied by w
 - Conclude that $\alpha \not\models \beta$
 - Conclude that $\alpha \models \beta$

- Given knowledge α and query β
 - For everyignossibole: Wonlderw
 - If α is satisfied by w WeChat: cstutores
 - ullet If eta is not satisfied by w
 - Conclude that $\alpha \not\models \beta$
 - Conclude that $\alpha \models \beta$

Computing Entailment

```
AIMA Fig. 7.10
boolean TT Entails? (KB, \alpha)
   symbols \longleftarrow proposition symbols used in KB and \alpha
   return TT_Check_All(KB, \alpha, symbols, \{\})
boolean TT_Check_AlhlysktBtoccs.symbols, model)
   if empty?(symbols) thenat: cstutores
      if PL True?(KB, model) then return PL True(\alpha, model)
      else return true // when KB is false, always return true
   else
      P \leftarrow \texttt{first}(symbols)
      rest \leftarrow rest(symbols)
      return TT Check All(KB, \alpha, rest, model \cup \{P=true\})
                && TT Check All(KB, \alpha, rest, model \cup \{P=false\})
```

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- Given knowledge α and query β
 - For everyignossibole: Wonlderw
 - If α is satisfied by w WeChat: cstutores
 - ullet If eta is not satisfied by w
 - Conclude that $\alpha \not\models \beta$
 - Conclude that $\alpha \models \beta$

| $P_{1,1}$ | $P_{1,2}$ | 4 | $OK_{1,1}$ | $OK_{2,1}$ | R_1 | R_2 | | $\neg B_{1,1}$ | $\neg S_{1,1}$ | $OK_{2,1}$ |
|-----------|-----------|-----|--------------|------------|-----------|-------|------|----------------|----------------|------------|
| F | F | ••• | K ssi | gnment | Project | Exam | Help | ••• | Т | |
| | | | | https://t | utores.c | om | | | | |
| F | F | ••• | Т | WeCha | t: cstuto | orcs | ••• | ••• | Т | Т |
| ••• | | | | | ••• | | | | | |
| Т | Т | ••• | F | Т | F | ••• | ••• | ••• | F | |
| Т | Т | ••• | Т | F | T | F | ••• | ••• | Т | |
| Т | Т | ••• | T | Т | T | Т | | ••• | F | |

| $P_{1,1}$ | $P_{1,2}$ | * | $OK_{1,1}$ | $OK_{2,1}$ | R_1 | R_2 | ••• | $\neg B_{1,1}$ | $\neg S_{1,1}$ | $OK_{2,1}$ |
|-----------|-----------|----------|------------|------------|-----------|--------|-------------------|----------------|----------------|------------|
| F | F | ••• | Essi | gnment | Project | Exam : | Help [*] | ••• | Т | |
| ••• | | | | nttps://t | utores.c | om | | | | |
| F | F | ••• | Т | WeCha | t: cstuto | orcs | ••• | | Т | Т |
| ••• | | | | | ••• | | | | | |
| Т | Т | • • • | F | T | F | ••• | ••• | ••• | F | |
| Т | Т | ••• | Т | F | Т | F | ••• | ••• | Т | |
| Т | Т | ••• | T | Т | Т | Т | | ••• | F | |

| $P_{1,1}$ | $P_{1,2}$ | | $OK_{1,1}$ | $OK_{2,1}$ | R_1 | R_2 | ••• | $\neg B_{1,1}$ | $\neg S_{1,1}$ | $OK_{2,1}$ |
|-----------|-----------|-----|--------------|------------|-----------|-------|------|----------------|----------------|------------|
| F | F | ••• | E ssi | gnment | Project | Exam | Help | ••• | Т | |
| ••• | | | | https://t | utores.c | om | | | | |
| F | F | ••• | Т | WeCha | t: cstuto | orcs | ••• | ••• | Т | Т |
| ••• | | | | | ••• | | | | | |
| Т | Т | ••• | F | Т | F | ••• | ••• | ••• | F | |
| Т | Т | ••• | Т | F | Т | F | ••• | ••• | Т | |
| Т | Т | ••• | T | Т | Т | Т | | ••• | F | |

| $P_{1,1}$ | $P_{1,2}$ | 4 | $OK_{1,1}$ | $OK_{2,1}$ | R_1 | R_2 | | $\neg B_{1,1}$ | $\neg S_{1,1}$ | $OK_{2,1}$ |
|-----------|-----------|-------|--------------|------------|-----------|-------|-------------------|----------------|----------------|------------|
| F | F | ••• | E ssi | gnment | Project | Exam | Help [*] | • • • | T | |
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| F | F | ••• | Т | WeCha | t: cstuto | rcsT | ••• | | Т | Т |
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| T | Т | • • • | F | T | F | ••• | | | F | |
| T | Т | ••• | Т | F | Т | F | | ••• | Т | |
| T | Т | ••• | T | Т | Т | Т | | ••• | F | |

n propositions m sentences, O(k) connectives

| $P_{1,1}$ | $P_{1,2}$ | 4 | $OK_{1,1}$ | $OK_{2,1}$ | R_1 | R_2 | | $\neg B_{1,1}$ | $\neg S_{1,1}$ | $OK_{2,1}$ |
|-----------|-----------|-------|------------|------------|-----------|-------|-------------------|----------------|----------------|------------|
| F | F | ••• | Essi | gnment | Project | Exam | Help [*] | ••• | Т | |
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| F | F | ••• | Т | WeCha | t: cstute | orcs | ••• | ••• | Т | Т |
| ••• | | | | | ••• | | | | | |
| Т | Т | • • • | F | Т | F | ••• | ••• | ••• | F | |
| Т | Т | ••• | Т | F | Т | F | ••• | • • • | Т | |
| Т | Т | ••• | Т | Т | Т | Т | | ••• | F | |

 $(2^n mk)$ Intractable!

- α entails β : $\alpha \models \beta$
 - Every madelneft rajist elso reinhodel of β
 - Whenever α is true, so is β

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- β is true in every world consistent with α
- $Models(\alpha) \subseteq Models(\beta)$
- β logically follows from α

co-NP-complete!

Propositional Logic

- Programming language for knowledge
- Factored representation (Beglean CSP)
 - Propositionspsconnectives, sentences
- Possible worlds hatis hability, models
- Entailment: $\alpha \models \beta$
 - Every model of α is a model of β
 - Model checking intractable!

For next time: Assignment Project Exam Help

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AIMA Ch. 7.5