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Introduction to  
**Artificial Intelligence**  
with Python

Knowledge

# knowledge-based agents

agents that reason by operating on  
internal representations of knowledge

**If it didn't rain, Harry visited Hagrid today.**

Harry visited Hagrid or Dumbledore today, but not both.

Harry visited Dumbledore today.

**Harry did not visit Hagrid today.**

**It rained today.**

# Logic

# sentence

an assertion about the world  
in a knowledge representation language

# Propositional Logic



# Proposition Symbols

$P$

$Q$

$R$

# Logical Connectives

$\neg$

not

$\wedge$

and

$\vee$

or

$\rightarrow$

implication

$\leftrightarrow$

biconditional

# Not ( $\neg$ )

$P$	$\neg P$
false	true
true	false

# And ( $\wedge$ )

$P$	$Q$	$P \wedge Q$
false	false	false
false	true	false
true	false	false
true	true	true

# Or ( $\vee$ )

$P$	$Q$	$P \vee Q$
false	false	false
false	true	true
true	false	true
true	true	true

# Implication ( $\rightarrow$ )

$P$	$Q$	$P \rightarrow Q$
false	false	true
false	true	true
true	false	false
true	true	true

# Biconditional ( $\leftrightarrow$ )

$P$	$Q$	$P \leftrightarrow Q$
false	false	true
false	true	false
true	false	false
true	true	true

# model

assignment of a truth value to every  
propositional symbol (a "possible world")



**model**

*P*: It is raining.

*Q*: It is a Tuesday.

$\{P = \text{true}, Q = \text{false}\}$

# knowledge base

a set of sentences known by a  
knowledge-based agent

# Entailment

$$\alpha \models \beta$$

In every model in which sentence  $\alpha$  is true,  
sentence  $\beta$  is also true.

**If it didn't rain, Harry visited Hagrid today.**

Harry visited Hagrid or Dumbledore today, but not both.

Harry visited Dumbledore today.

**Harry did not visit Hagrid today.**

**It rained today.**

# inference

the process of deriving new sentences  
from old ones

$P$ : It is a Tuesday.

$Q$ : It is raining.

$R$ : Harry will go for a run.

KB:  $(P \wedge \neg Q) \rightarrow R$        $P$        $\neg Q$

Inference:  $R$

# Inference Algorithms

Does  
 $\text{KB} \models \alpha$   
?



# Model Checking

# Model Checking

- To determine if  $\mathbf{KB} \models \alpha$ :
  - Enumerate all possible models.
  - If in every model where  $\mathbf{KB}$  is true,  $\alpha$  is true, then  $\mathbf{KB}$  entails  $\alpha$ .
  - Otherwise,  $\mathbf{KB}$  does not entail  $\alpha$ .

$P$ : It is a Tuesday.       $Q$ : It is raining.       $R$ : Harry will go for a run.

KB:  $(P \wedge \neg Q) \rightarrow R$        $P$        $\neg Q$

Query:  $R$

$P$	$Q$	$R$	KB
false	false	false	
false	false	true	
false	true	false	
false	true	true	
true	false	false	
true	false	true	
true	true	false	
true	true	true	

$P$ : It is a Tuesday.       $Q$ : It is raining.       $R$ : Harry will go for a run.

KB:  $(P \wedge \neg Q) \rightarrow R$        $P$        $\neg Q$

Query:  $R$

$P$	$Q$	$R$	KB
false	false	false	false
false	false	true	false
false	true	false	false
false	true	true	false
true	false	false	false
true	false	true	true
true	true	false	false
true	true	true	false

$P$ : It is a Tuesday.       $Q$ : It is raining.       $R$ : Harry will go for a run.

KB:  $(P \wedge \neg Q) \rightarrow R$        $P$        $\neg Q$

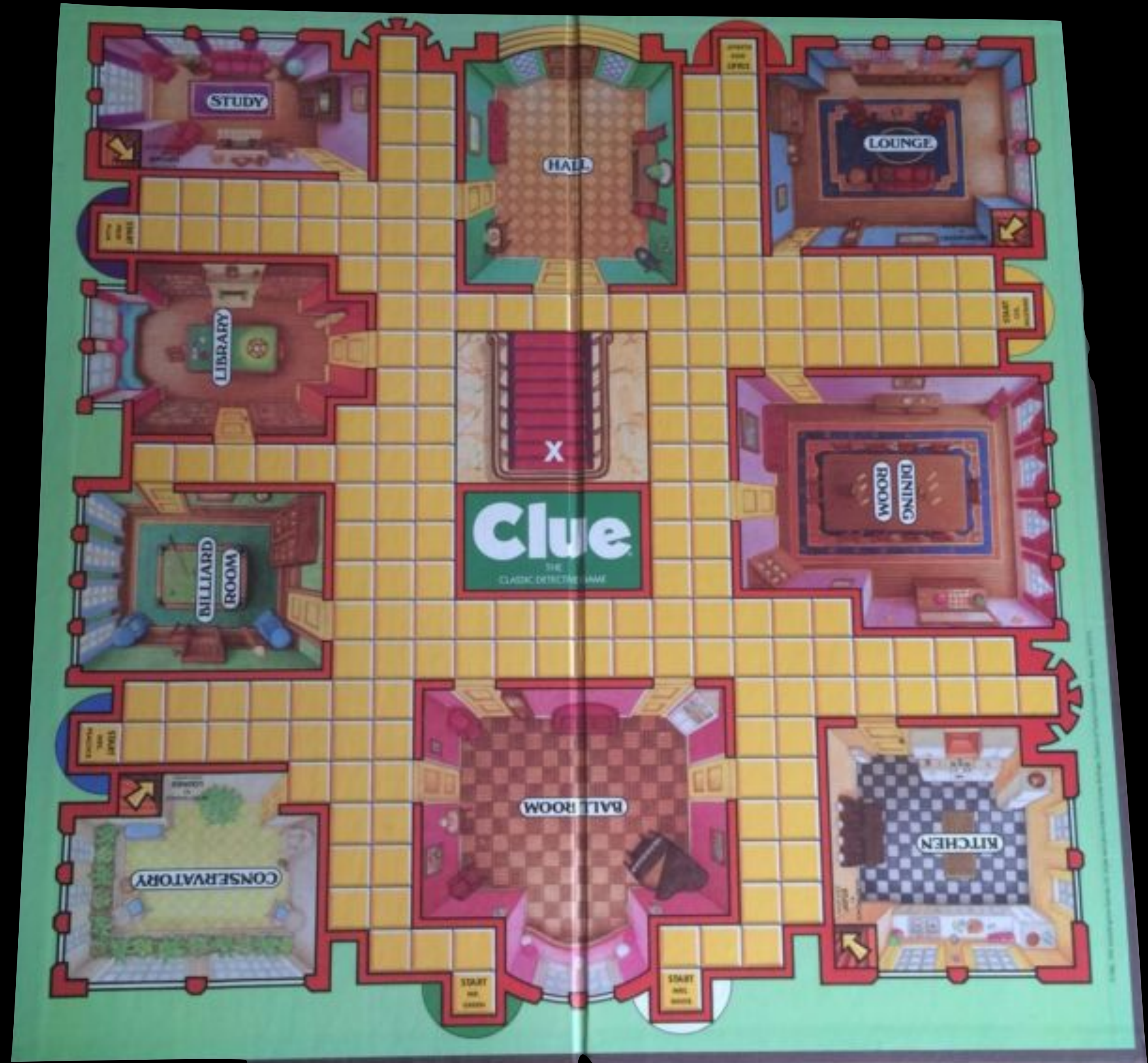
Query:  $R$

$P$	$Q$	$R$	KB
false	false	false	false
false	false	true	false
false	true	false	false
false	true	true	false
true	false	false	false
true	false	true	true
true	true	false	false
true	true	true	false

# Knowledge Engineering



# Clue





# Clue

## People

Col. Mustard

Prof. Plum

Ms. Scarlet

## Rooms

Ballroom

Kitchen

Library

## Weapons

Knife

Revolver

Wrench



# Clue

People


Rooms


Weapons


# Clue

People


Rooms


Weapons


# People


# Rooms


# Weapons




People



Rooms



Weapons



# Clue

## Propositional Symbols

*mustard*

*ballroom*

*knife*

*plum*

*kitchen*

*revolver*

*scarlet*

*library*

*wrench*

# Clue

*(mustard ∨ plum ∨ scarlet)*

*(ballroom ∨ kitchen ∨ library)*

*(knife ∨ revolver ∨ wrench)*

$\neg plum$

$\neg mustard \vee \neg library \vee \neg revolver$

# Logic Puzzles

- Gilderoy, Minerva, Pomona and Horace each belong to a different one of the four houses: Gryffindor, Hufflepuff, Ravenclaw, and Slytherin House.
- Gilderoy belongs to Gryffindor or Ravenclaw.
- Pomona does not belong in Slytherin.
- Minerva belongs to Gryffindor.

# Logic Puzzles

## Propositional Symbols

*GilderoyGryffindor*  
*GilderoyHufflepuff*  
*GilderoyRavenclaw*  
*GilderoySlytherin*

*PomonaGryffindor*  
*PomonaHufflepuff*  
*PomonaRavenclaw*  
*PomonaSlytherin*

*MinervaGryffindor*  
*MinervaHufflepuff*  
*MinervaRavenclaw*  
*MinervaSlytherin*

*HoraceGryffindor*  
*HoraceHufflepuff*  
*HoraceRavenclaw*  
*HoraceSlytherin*



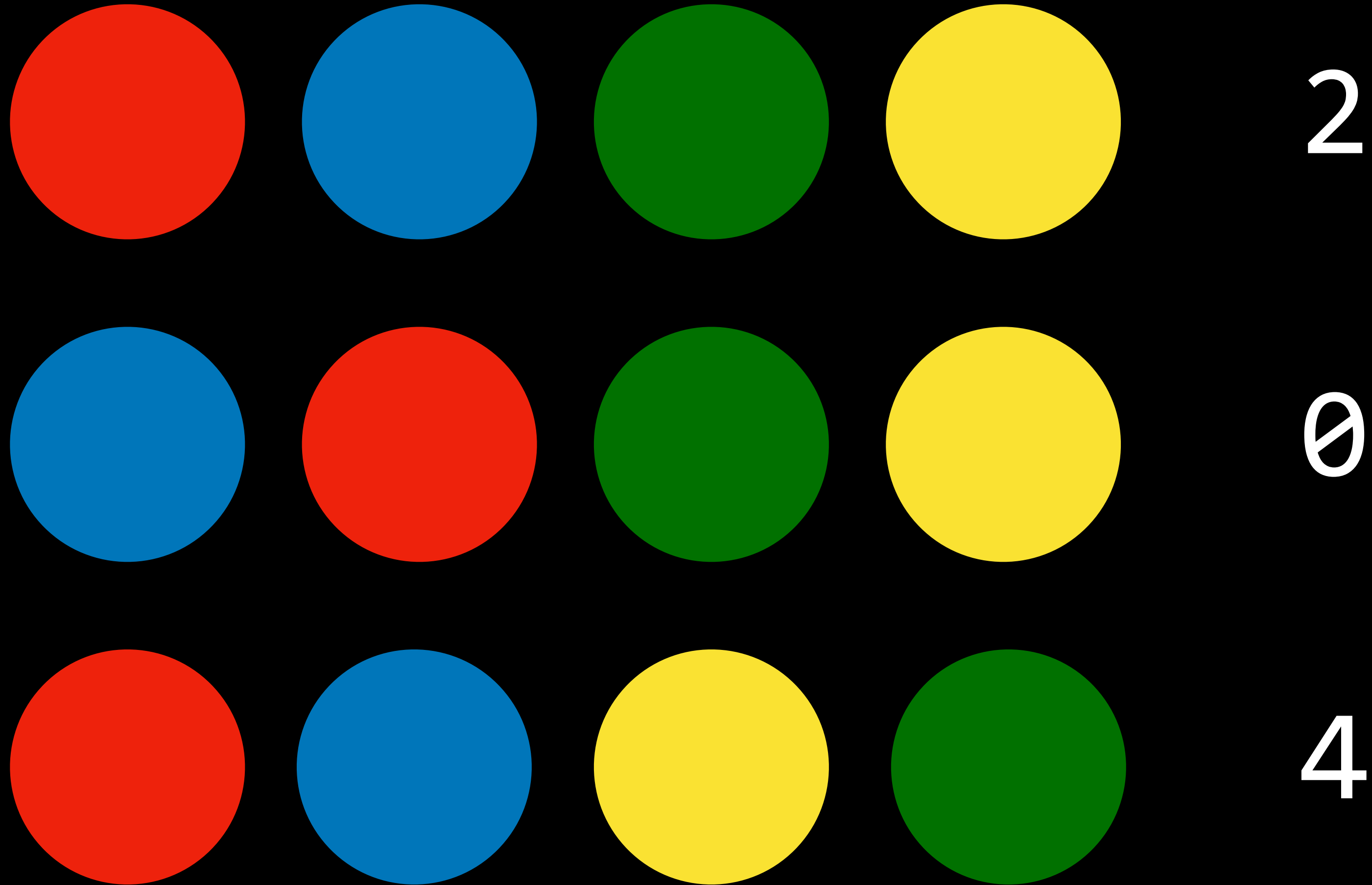
# Logic Puzzles

*(PomonaSlytherin  $\rightarrow$   $\neg$  PomonaHufflepuff)*

*(MinervaRavenclaw  $\rightarrow$   $\neg$  GilderoyRavenclaw)*

*(GilderoyGryffindor  $\vee$  GilderoyRavenclaw)*

# Mastermind



# Inference Rules

# Modus Ponens

If it is raining, then Harry is inside.

It is raining.

---

Harry is inside.

# Modus Ponens

$$\alpha \rightarrow \beta$$

$$\alpha$$



$$\beta$$

# And Elimination

Harry is friends with Ron and Hermione.

---

Harry is friends with Hermione.

# And Elimination

$$\alpha \wedge \beta$$

---

$$\alpha$$

# Double Negation Elimination

It is not true that Harry did not pass the test.

---

Harry passed the test.



# Double Negation Elimination

$$\neg(\neg\alpha)$$

---

$$\alpha$$

# Implication Elimination

If it is raining, then Harry is inside.

---

It is not raining or Harry is inside.

# Implication Elimination

$$\alpha \rightarrow \beta$$

---

$$\neg \alpha \vee \beta$$

# Biconditional Elimination

It is raining if and only if Harry is inside.

---

If it is raining, then Harry is inside,  
and if Harry is inside, then it is raining.

# Biconditional Elimination

$$\alpha \leftrightarrow \beta$$

---

$$(\alpha \rightarrow \beta) \wedge (\beta \rightarrow \alpha)$$

# De Morgan's Law

It is not true that both  
Harry and Ron passed the test.

---

Harry did not pass the test  
or Ron did not pass the test.

# De Morgan's Law

$$\neg(\alpha \wedge \beta)$$

---

$$\neg\alpha \vee \neg\beta$$

# De Morgan's Law

It is not true that  
Harry or Ron passed the test.

---

Harry did not pass the test  
and Ron did not pass the test.



# De Morgan's Law

$$\neg(\alpha \vee \beta)$$

---

$$\neg\alpha \wedge \neg\beta$$

# Distributive Property

$$(a \wedge (\beta \vee \gamma))$$

---

$$(a \wedge \beta) \vee (a \wedge \gamma)$$

# Distributive Property

$$(a \vee (\beta \wedge \gamma))$$

---

$$(a \vee \beta) \wedge (a \vee \gamma)$$

# Search Problems

- initial state
- actions
- transition model
- goal test
- path cost function

# Theorem Proving

- initial state: starting knowledge base
- actions: inference rules
- transition model: new knowledge base after inference
- goal test: check statement we're trying to prove
- path cost function: number of steps in proof

# Resolution

$(\text{Ron is in the Great Hall}) \vee (\text{Hermione is in the library})$

Ron is not in the Great Hall

---

Hermione is in the library

$$P \vee Q$$

$$\neg P$$

---

$$Q$$



$$P \vee Q_1 \vee Q_2 \vee \dots \vee Q_n$$

$$\neg P$$

---


$$Q_1 \vee Q_2 \vee \dots \vee Q_n$$

$(\text{Ron is in the Great Hall}) \vee (\text{Hermione is in the library})$

$(\text{Ron is not in the Great Hall}) \vee (\text{Harry is sleeping})$

---

$(\text{Hermione is in the library}) \vee (\text{Harry is sleeping})$

$$P \vee Q$$

$$\neg P \vee R$$

---

$$Q \vee R$$

$$P \vee Q_1 \vee Q_2 \vee \dots \vee Q_n$$

$$\neg P \vee R_1 \vee R_2 \vee \dots \vee R_m$$

---


$$Q_1 \vee Q_2 \vee \dots \vee Q_n \vee R_1 \vee R_2 \vee \dots \vee R_m$$

# clause

a disjunction of literals

e.g.  $P \vee Q \vee R$

# conjunctive normal form

logical sentence that is a conjunction of clauses

e.g.  $(A \vee B \vee C) \wedge (D \vee \neg E) \wedge (F \vee G)$

# Conversion to CNF

- Eliminate biconditionals
  - turn  $(\alpha \leftrightarrow \beta)$  into  $(\alpha \rightarrow \beta) \wedge (\beta \rightarrow \alpha)$
- Eliminate implications
  - turn  $(\alpha \rightarrow \beta)$  into  $\neg\alpha \vee \beta$
- Move  $\neg$  inwards using De Morgan's Laws
  - e.g. turn  $\neg(\alpha \wedge \beta)$  into  $\neg\alpha \vee \neg\beta$
- Use distributive law to distribute  $\vee$  wherever possible

# Conversion to CNF

$$(P \vee Q) \rightarrow R$$

$$\neg(P \vee Q) \vee R$$

eliminate implication

$$(\neg P \wedge \neg Q) \vee R$$

De Morgan's Law

$$(\neg P \vee R) \wedge (\neg Q \vee R)$$

distributive law



# Inference by Resolution

$$P \vee Q$$

$$\neg P \vee R$$

---

$$(Q \vee R)$$

$$P \vee Q \vee S$$

$$\neg P \vee R \vee S$$

---

$$(Q \vee S \vee R \vee S)$$

$$P \vee Q \vee S$$

$$\neg P \vee R \vee S$$

---

$$(Q \vee R \vee S)$$

$P$

$\neg P$



$()$

# Inference by Resolution

- To determine if  $\text{KB} \models \alpha$ :
  - Check if  $(\text{KB} \wedge \neg\alpha)$  is a contradiction?
    - If so, then  $\text{KB} \models \alpha$ .
    - Otherwise, no entailment.

# Inference by Resolution

- To determine if  $\text{KB} \models \alpha$ :
  - Convert  $(\text{KB} \wedge \neg\alpha)$  to Conjunctive Normal Form.
  - Keep checking to see if we can use resolution to produce a new clause.
    - If ever we produce the **empty** clause (equivalent to False), we have a contradiction, and  $\text{KB} \models \alpha$ .
    - Otherwise, if we can't add new clauses, no entailment.

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A)$$



# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad \underline{(\neg B \vee C)} \quad \underline{(\neg C)} \quad (\neg A)$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad \underline{(\neg B \vee C)} \quad \underline{(\neg C)} \quad (\neg A) \quad (\neg B)$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A) \quad (\neg B)$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$\underline{(A \vee B)} \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A) \quad \underline{(\neg B)}$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$\underline{(A \vee B)} \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A) \quad \underline{(\neg B)} \quad (A)$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A) \quad (\neg B) \quad (A)$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad \underline{(\neg A)} \quad (\neg B) \quad \underline{(A)}$$

# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad \underline{(\neg A)} \quad (\neg B) \quad \underline{(A)} \quad ()$$



# Inference by Resolution

Does  $(A \vee B) \wedge (\neg B \vee C) \wedge (\neg C)$  entail  $A$ ?

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

$$(A \vee B) \quad (\neg B \vee C) \quad (\neg C) \quad (\neg A) \quad (\neg B) \quad (A) \quad ()$$

# First-Order Logic

# Propositional Logic

## Propositional Symbols

*MinervaGryffindor*

*MinervaHufflepuff*

*MinervaRavenclaw*

*MinervaSlytherin*

...

# First-Order Logic

Constant Symbol

*Minerva*

*Pomona*

*Horace*

*Gilderoy*

*Gryffindor*

*Hufflepuff*

*Ravenclaw*

*Slytherin*

Predicate Symbol

*Person*

*House*

*BelongsTo*

# First-Order Logic

*Person(Minerva)*

Minerva is a person.

*House(Gryffindor)*

Gryffindor is a house.

$\neg$ *House(Minerva)*

Minerva is not a house.

*BelongsTo(Minerva, Gryffindor)*

Minerva belongs to Gryffindor.

# Universal Quantification

# Universal Quantification

$$\forall x. \textit{BelongsTo}(x, \textit{Gryffindor}) \rightarrow \\ \neg \textit{BelongsTo}(x, \textit{Hufflepuff})$$

For all objects  $x$ , if  $x$  belongs to Gryffindor,  
then  $x$  does not belong to Hufflepuff.

Anyone in Gryffindor is not in Hufflepuff.

# Existential Quantification



# Existential Quantification

$$\exists x. \textit{House}(x) \wedge \textit{BelongsTo}(\textit{Minerva}, x)$$

There exists an object  $x$  such that  
 $x$  is a house and Minerva belongs to  $x$ .

Minerva belongs to a house.

# Existential Quantification

$$\forall x. \textit{Person}(x) \rightarrow (\exists y. \textit{House}(y) \wedge \textit{BelongsTo}(x, y))$$

For all objects  $x$ , if  $x$  is a person, then there exists an object  $y$  such that  $y$  is a house and  $x$  belongs to  $y$ .

Every person belongs to a house.

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