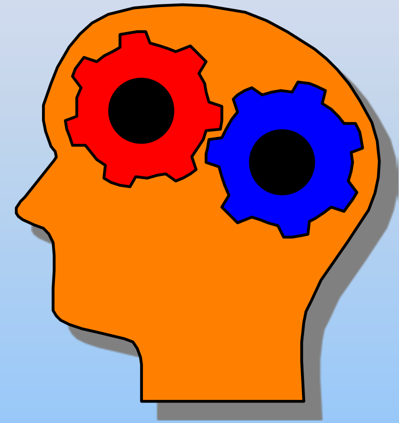
ARTIFICIAL INTELLIGENCE



CSC304

CZ3005

School of Computer Engineering
Nanyang Technological University

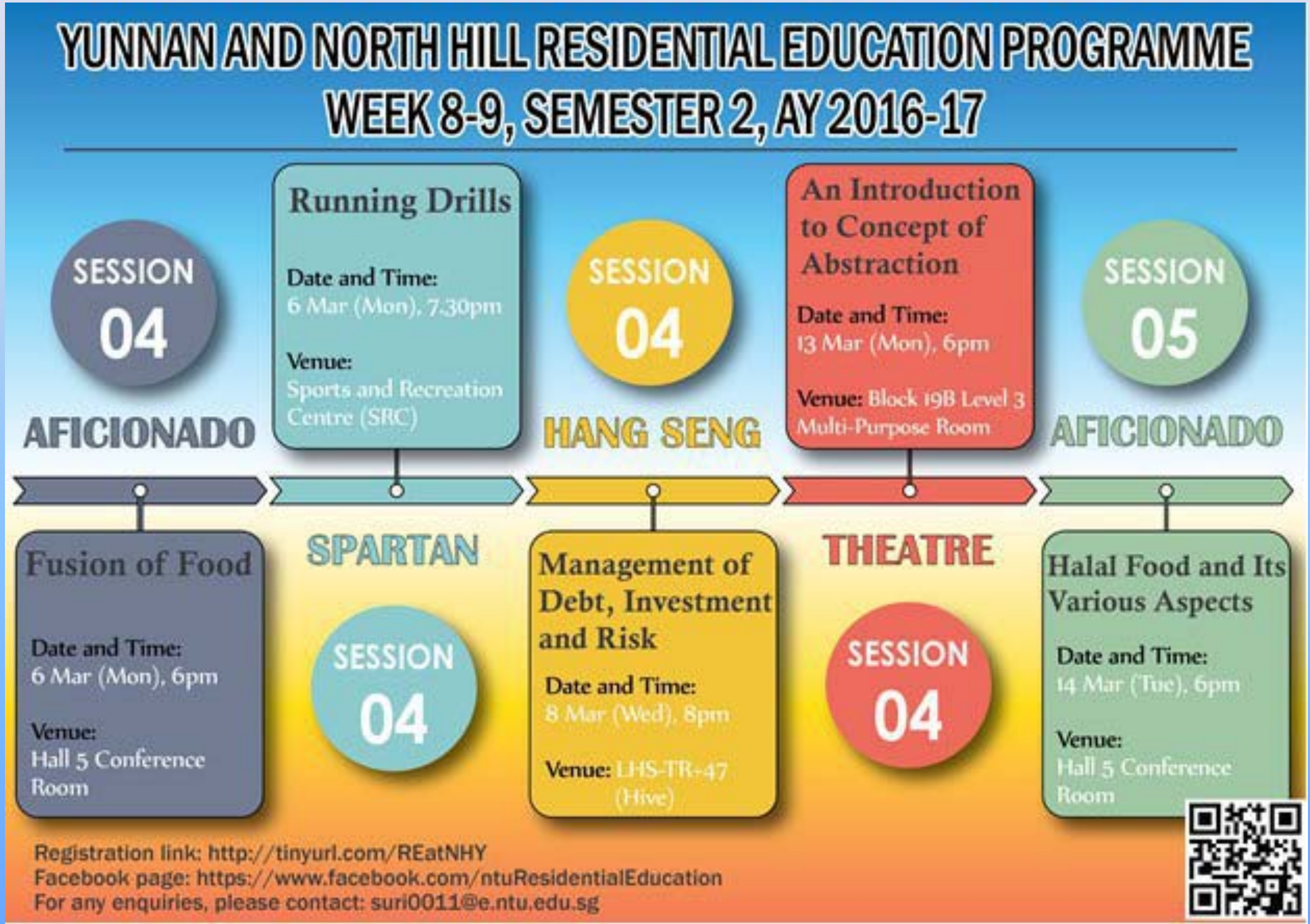
- I Artificial Intelligence
- II Problem Solving
- **III Knowledge and Reasoning**
- IV Acting Logically
- V Uncertain Knowledge and Reasoning
- VI Learning
- VII Communicating, Perceiving and Acting
- VIII Conclusions

Profile of Lecturer

- Dr Chai Quek
- Ph.D. – H.W. Edinburgh 1990
  - An Intelligent Supervisory Control Schema
- Area of Research: Learning Systems, Neural Network, Fuzzy System, Hybrid Fuzzy Neural Systems, Softcomputing, Computational Intelligence
- Application Areas: Computational Finance, Biomedical Engg, Intelligent Control, Intelligent Education, Soft modelling, (cognitive) sentiment mining
- Students groomed: over 12 gold medalists, 30 Ph.D.s, MSc, MEng etc.
- Hall 7 Senior Hall Fellow, Binjai Hall SFiR, Northhill and Yunnan RE Lead, Assoc Chair (Students) SCSE

Residential Education

RE@Northill and Yunnan



Part III – Knowledge and Reasoning

- **6 Agents that Reason Logically**
  - Knowledge-based Agents. – Representations.
  - Propositional Logic. – The Wumpus World.
- **7 First-Order Logic**
  - Syntax and Semantics. – Using First-Order Logic.
  - Logical Agents. – Representing Changes.
  - Deducing Properties of the World.
  - Goal-based Agents.
- **8 Building a Knowledge Base**
  - Knowledge Engineering. – General Ontology.

Part III – Knowledge and Reasoning

- **9 Inference in First-Order Logic**
  - Inference Rules. – Generalised Modus Ponens.
  - Forward and Backward Chaining. – Resolution.
- **10 Example classes - Prolog as KBS**
  - Starting week 10 – intro
  - Starting week 12 – assignment Wk 14 (Venue TBA) **(marks to be part of continuous assessments)**

6 – AGENTS THAT REASON LOGICALLY

"In which we design agents that can form representations of the world, use a process of inference to derive new representations about the world, and use these new representations to deduce what to do."

Brain Inspired Representation

- **Learning memory – construction of knowledge from data**
  - Hippocampus – fuzzy rule learning using neural network
  - Cerebellum – calibration of motion action
  - Supervised and unsupervised learning
  - Reinforcement learning
  - Long term association
  - Parallel firing of rules
  - Compactness of rules
  - Forgetting of rules

Human Inspired Representation

- **Expert representation modelled around the cognitive structure of human reasoning**
  - Symbolic – Logic
  - Semantic – “Lingusitic”, fuzzy logic
- **Cognitive structure**
  - Long Term
  - Short Term
  - Inference Mechanism
  - Soundness and Completeness

The Knowledge-Based Approach

- **Agents that *know***
  - – Achieve competence by being told new knowledge or by learning
  - – Achieve adaptability by updating their knowledge
  - – > *Knowledge representation*
    - State of the world, properties and evolution of the world; goals of the agent, actions and their effect
- **Agents that *reason***
  - – Use knowledge to deduce course of actions
  - – > *Knowledge inference*

Logic

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Knowledge-Based Agents

- **Knowledge base (KB)**
  - Set of <u>sentences</u> i.e., representations of facts (DB)
  - Knowledge representation language
- **Adding and querying knowledge**
  - **Tell**: add a sentence to the KB
  - **Ask**: retrieve knowledge from the KB
    - Answers must *follow* from what has been **Tell**'ed (told)
- **Inference mechanism**
  - Role: determine what follows from the KB

Problem Formulation of KBS

- **Knowledge Based System**
  - States: Instances of the KB (sets of sentences)
    –> Use **Tell** to build the KB

    e.g. Tell(KB, "Smoke $\Rightarrow$ Fire")
    Tell(KB, "Fire $\Rightarrow$ Call_911")
    …
    Tell(KB, "Smoke")
  - Operators: Add / Infer a new sentence
  - Goal: Answer a query
    –> Use **Ask** to query the KB

    e.g. Ask(KB, "**?** Call_911")

A Generic Knowledge-Based Agent

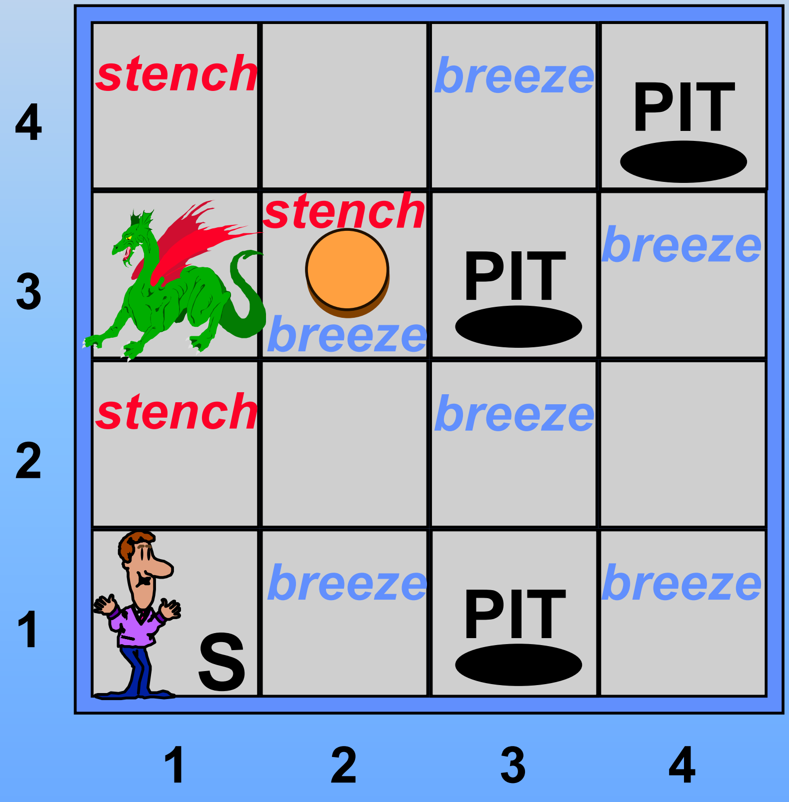
```
function KB-Agent (percept) returns action
        static  KB,              // a knowledge base
                t                // a time counter, initially 0

      Tell (KB, Make-Percept-Sentence (percept, t))
      action ← Ask (KB, Make-Action-Query (percept, t))
      Tell (KB, Make-Action-Sentence (action, t))
      t ← t + 1
      return action
```

– > 3 steps: interpretation, inference, execution

– > KB: background knowledge (observed)
+ acquired information (deduced)

Example: the Wumpus World

- **Problem description (PAGE)**
  - Environment
    - Grid of squares, walls;
    - Agent, gold, pits, wumpus.
  - Goal
    - Find the gold, return to S at [1,1].
  - Percepts
    - A list of 5 symbols, e.g. [Stench, Breeze, Glitter, Bump, Scream];
    - Agent's location *not* perceived.
  - Actions
    - Go-Forward, Turn-Left, Turn-Right, Grab, Shoot (1 arrow only), Climb.



Levels of Knowledge

- **Epistemological level**
  - Declarative description of knowledge
    - e.g. facts: “there is smoke in the kitchen”, “it is not warm enough”
      rules: “if there is smoke then there must be a fire”
- **Logical level**
  - Logical encoding of knowledge (into sentences)
    - e.g. facts: Smoke; rules: Implies(Smoke, Fire)
- **Implementation level**
  - Physical representation of knowledge (sentences)
    - e.g. - the string “Implies(Smoke, Fire)”, or
      - a “1” entry in a 2-dimensional array: Implies[X,Y]

Tell

Ask

The Wumpus World

- **Problem description (cont'd)**
  - Initial state
    - Agent at [1,1]; gold, pits and wumpus in <u>random</u> squares.
  - Path-cost
    - Climbing out with the gold: +1000 (without: 0) • Each action: –1
    - Getting killed (pit or wumpus): –10000
  - <u>Knowledge</u>
    - "In all squares adjacent to the one where the wumpus is, the agent will perceive a <u>stench</u>."
    - "In all squares adjacent to a pit, the agent will perceive a <u>breeze</u>."
    - In the square where the gold is, the agent will perceive a <u>glitter</u>."
    - When walking into a wall, the agent will perceive a <u>bump</u>."
    - When the wumpus is killed, the agent will perceive a <u>scream</u>."

Acting and Reasoning in the Wumpus World

(0) Initial state
[nil, nil, nil, nil, nil]

4				
3				
2	OK			
1	A OK	OK		
	1	2	3	4

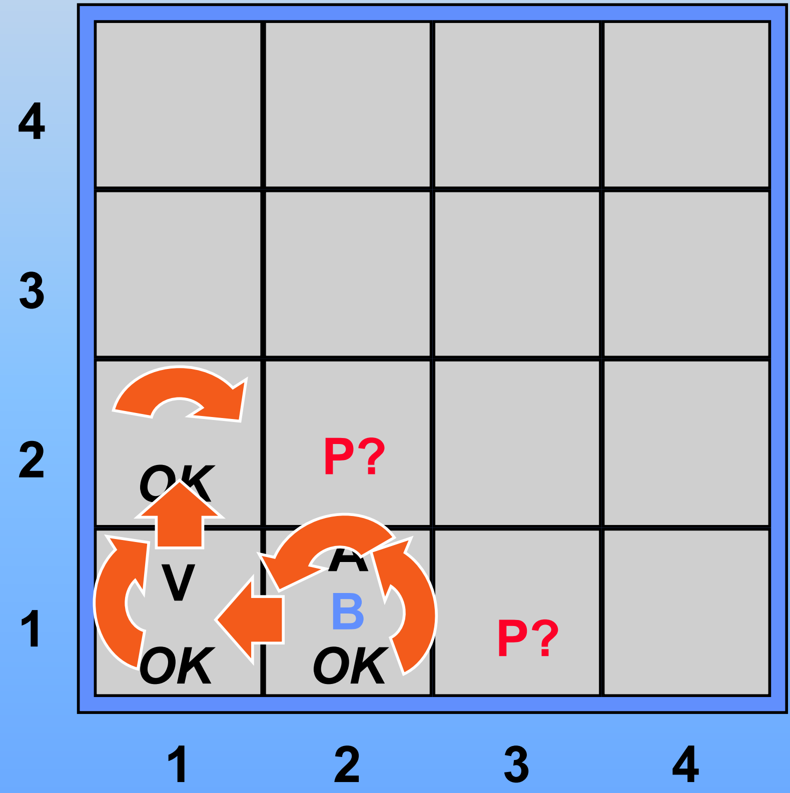
(1) after {F}
[nil, Breeze, nil, nil, nil]

4				
3				
2	OK	P?		
1	V OK	A B OK	P?	
	1	2	3	4

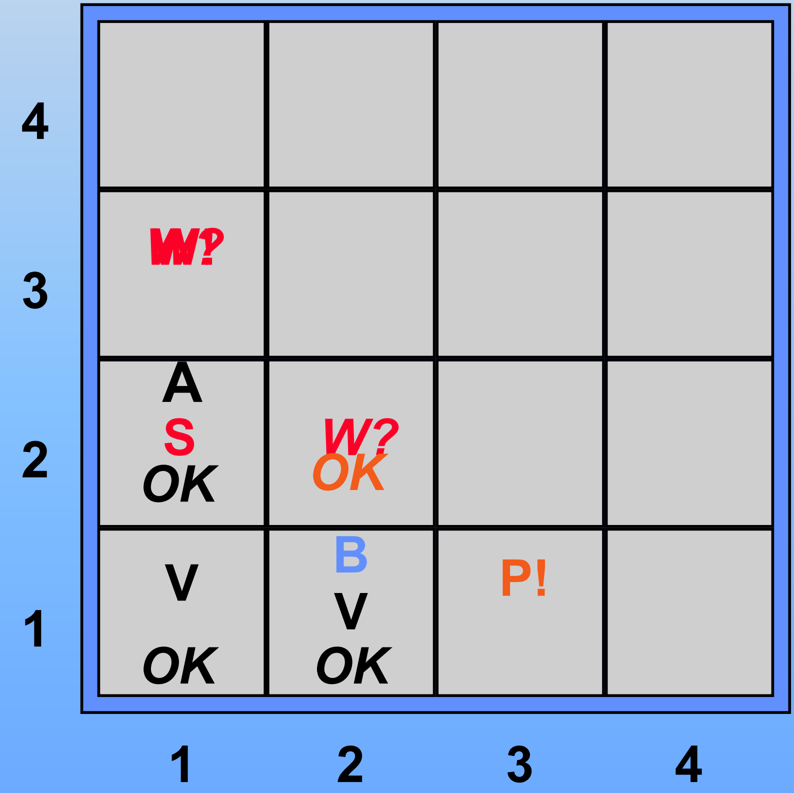
A = Agent
B = Breeze
G = Glitter, Gold
OK = Safe square
P = Pit
S = Stench
V = Visited
W = Wumpus

Acting and Reasoning in the Wumpus World

(1) after {F}
[nil, Breeze, nil, nil, nil]



(6) after {F, L, L, F, R, F}
[Stench , nil, nil, nil, nil]



A = Agent
B = Breeze
G = Glitter, Gold
OK = Safe square
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S = Stench
V = Visited
W = Wumpus

Acting and Reasoning in the Wumpus World

(6) after {F, L, L, F, R, F}
[Stench , nil, nil, nil, nil]

	1	2	3	4
4				
3	W!	*OK*		
2	S *OK*	*OK*	*OK*	
1	V *OK*	B V *OK*	P!	

(10) after {F, L, L, F, R, F ,R, F, L, F}
[Stench, Breeze, Glitter, nil, nil]

	1	2	3	4
4		P?		
3	W!	A S G B	P?	
2	S V *OK*	V *OK*	*OK*	
1	V *OK*	B V *OK*	P!	

A = Agent
B = Breeze
G = Glitter, Gold
OK = Safe square
P = Pit
S = Stench
V = Visited
W = Wumpus

end

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Knowledge Representations

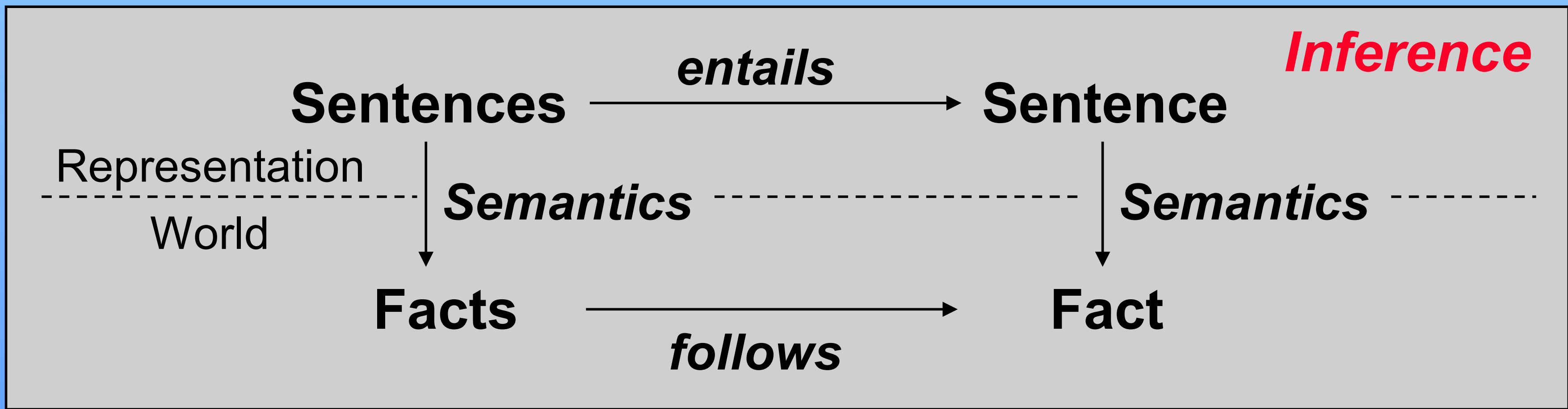
- **Knowledge representation (KR)**
  - KB: set of sentences –> need to
  - Express knowledge in a (computer-) tractable form
- **Knowledge representation language**
  - Syntax – implementation level
    - Possible configurations that constitute sentences (example)
  - Semantics – knowledge level

Language Representation

    - Facts of the world the sentences refer to
    - e.g. 1 language of arithmetics: x, y numbers
      sentence: "$x \geq y$", semantics: "greater or equal"
    - e.g. 2 language of genomics: x, y chromosones
      x.x means female and x.y means male

Reasoning and Logic

- **Logic**
  - Representation + Inference = Logic
    - Where representation = syntax + semantics
- **Reasoning**
  - Construction of new sentences from existing ones
- **Entailment as logical inference**

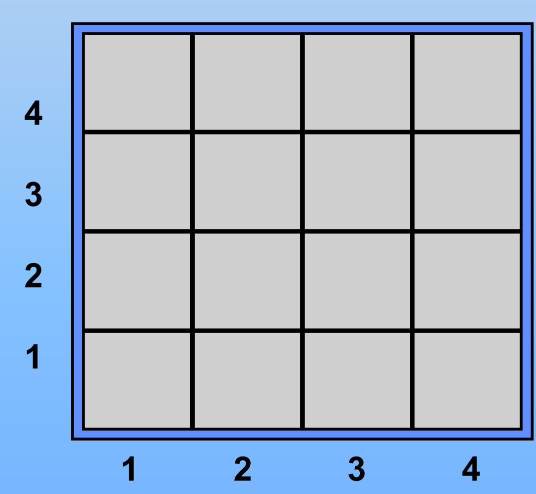


Deduction and Induction

- **Mechanical reasoning**
  - Example
    - If a chord sequence is tonal, then it can be generated by a context-sensitive grammar.
    - The twelve-bar blues has a chord sequence that is tonal. |-
    - The twelve-bar blues has a chord sequence that can be generated by a context-sensitive grammar.
- **Deductive inference**
  - KB: Monday ⇒ Work, Monday |- Work *sound (MP)*
- **Inductive inference**
  - KB: Monday ⇒ Work, Work |- Monday *unsound!*
  - Generalization e.g., *"all swans are white …" discovered* *counnter example by William de Vlamingh*

Entailment and Inference

- **Entailment**
  - Generate sentences that are necessarily true, given that the existing sentences are true
  - Notation: KB $\models \alpha$
    - e.g. Wumpus world:
      { "$\neg$S(1,1)", "$\neg$B(1,1)" } $\models$ "OK(2,1)"
      Arithmetics:
      { "$x \geq y$", "$y \geq z$" } $\models$ "$x \geq z$"



- **Inference**
  - **Tell**, given KB: (KB $\models \alpha$) !
  - **Ask**, given KB and α: (KB $\models \alpha$) ?

Properties of Inference

  - *Can be described by the sentences it derives, KB* |= α_I
- **Soundness**
  - Generate only entailed sentences
  - Proof: sequence of operations of a sound inference
    - Record of operations that generate a specific entailed sentence
      e.g. "Smoke ⇒ Fire" and "Smoke" |= "Fire"
      "Fire ⇒ Call_911" and "Fire" |= "Call_911"
- **Completeness**
  - A proof can be found for any entailed sentence
- **Proof theory**
  - Specify the reasoning operations that are sound

An Example of Sound Inference

- Sentence: x
  - Semantics: an expression; can be a single symbol or number, the concatenation of 2 expressions, etc.
- Sentence: $x\ y$
  - Semantics: an expression which refers to a quantity that is the <u>product</u> of the quantities referred to by each of the expressions
- Sentence: $x = y$
  - Semantics: the 2 expressions on each side of "**=**" refer to the same quantity

- A sound inference: from

$$\begin{matrix} E = mc^2 \\ T_1 \geq T_2 \end{matrix} \models E\,T_1 \geq mc^2\,T_2$$

Is this a Sound Inference?

– Sentence: x
  - Semantics: an expression; can be a single symbol or number, the concatenation of 2 expressions, etc.

– Sentence: $x\ y$
  - Semantics: an expression which refers to a quantity that is the <u>product</u> of the quantities referred to by each of the expressions

– Sentence: $x = y$
  - Semantics: the 2 expressions on each side of “**=**“ refer to the same quantity

– A sound inference? from $E = mc^2$

$$T_1 > T_2 \quad \models \quad E\ T_1 \geq mc^2\ T_2$$

Knowledge Representation Languages

- **Formal (programming) languages**
  - Good at describing algorithms and data structures
    - e.g. the Wumpus world as a 4x4 array, World[2,2] ← Pit
  - Poor at representing incomplete / uncertain information
    - e.g. “there is a pit in [2,2] or [3,1]”, or “…a wumpus *somewhere*”
  - > *not <u>expressive</u> enough*
- **Natural languages**
  - Very expressive (too much, thus very complex)
  - More appropriate for communication than representation
  - Suffer from ambiguity
    - e.g. “It’s hot!” – fantastic figure or fast selling S6
    - e.g. “small cats and dogs” compared to “– x + y”.

Properties of Representations

- *KR languages should combine the advantages of both programming and natural languages.*

- **Desired properties**
  - Expressive
    - Can represent everything we need to.
  - Concise
  - Unambiguous
    - Sentences have a unique interpretation.
  - Context independent
    - Interpretation of sentences depends on semantics only.
  - Effective
    - An inference procedure allows to create new sentences.

Properties of Semantics

- **Interpretation (meaning)**
  - *Correspondence between sentences and facts*
  - Arbitrary meaning, fixed by the writer of the sentence
    - e.g. Natural languages: meaning fixed by usage (cf. dictionary)
      LOL, OMG, ATM etc
    - exceptions: encrypted messages, codes (e.g. Morse) *chat*
  - Systematic relationship: compositional languages
    - *The meaning of a sentence is a function of the meaning of its parts.*
  - Truth value
    - A sentence make a claim about the world –> TRUE or FALSE
    - *Depends on the interpretation and the state of the world*
      - e.g. Wumpus world: S(1,2) true if means “Stench at [1,2]” and the world has a wumpus at either [1,3] or [2,2].

one
un
uno
yi
ichi
...
I
1
—
...

Properties of Inference

- **Definition**
  - *Inference (reasoning) is the process by which conclusions are reached*
  - Logical inference (deduction) is the process that implements entailment between sentences
- **Useful properties**
  - Valid sentence (tautology)
    - iff TRUE under all possible interpretations in all possible worlds.
      - e.g. “S or ¬ S” is valid, “S(2,1) or ¬ S(2,1)”, etc.
  - Satisfiable sentence
    - iff there is some interpretation in some world for which it is TRUE
      - e.g. “S and ¬ S” is unsatisfiable

Inference and Agent Programs

- **Inference in computers**
  - Does not know the interpretation the agent is using for the sentences in the KB
  - Does not know about the world (actual facts)
  - Knows only what appears in the KB (sentences)
    - e.g. Wumpus world: doesn't know the meaning of "OK", what a wumpus or a pit is, etc. – can only see: KB |= "[2,2] is OK"
  - > *Cannot reason informally*
    - does not matter, however, if KB |= "[2,2] is OK" is a valid sentence
- **Formal inference**
  - Can handle arbitrarily complex sentences, KB |= P

Different Logics

- **Formal logic**
  - Syntax
    - A set of rules for writing sentences
  - Semantics
    - A set of rules (constraints) for relating sentences to facts
  - Proof theory / inference procedure
    - A set of rules for deducing entailments of sentences
- **Propositional logic**
  - <u>Symbols</u>, representing propositions (facts – P, J, ¬C, - Peter, Jane, ¬Catherine)
  - Boolean <u>connectives</u>, combining symbols
    - e.g. “Hot” or “Hot and Humid”

Different Logics

- **First-order logic**
  - Objects and predicates (unary, binary, or n-ary) representing properties of and relations between objects
  - Variables, Boolean connectives and quantifiers
    - e.g. “Hot(x)”, “Hot(Air)” or ”Hot(Air) and Humid(Air)”
- **Temporal logic (Allen’s work)**
  - World ordered by a set of time points (intervals)
- **Probabilistic and fuzzy logic (IRIS) (Rules)**
  - Degrees of belief and truth in sentences
    - e.g. “Washington is a state” with belief degree 0.4, “a city” 0.6, ”Washington is a large city” with truth degree 0.6

Different Degrees of Truth

- *Q: Is there a tuna sandwich in the refrigerator?*
- *A: 0.5 !*

- **Probabilities**
  - There *is* or there *isn’t* (50% chance either way).
- **Measures**
  - There is *half* a tuna sandwich there.
- **Fuzzy answer**
  - There is *something* there, but it *isn't really* a tuna sandwich. Perhaps it is some other kind of sandwich, or a tuna salad with no bread...12-3-2015

The Commitments of Logics

Formal (KR) Language	**Ontological commitment** (what exists in the world)	**Epistemological commitment** (what an agent believes about facts)
Propositional logic	facts	true / false / unknown
First-order logic	facts, objects, relations	true / false / unknown
Temporal logic	facts, objects, rel., times	true / false / unknown
Probability logic	facts	degree of belief 0…1
Fuzzy logic	degrees of truth 0…1	degree of belief 0…1

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Elements of Propositional Logic

- **Symbols**
  - Logical constants: TRUE, FALSE
  - Propositional symbols: P, Q, etc.
  - Logical connectives: $\land$, $\lor$, $\Leftrightarrow$, $\Rightarrow$, $\neg$
  - Parentheses: ( )
- **Sentences**
  - Atomic sentences: constants, propositional symbols
  - Combined with connectives, e.g. $P \land Q \lor R$
    also wrapped in parentheses, e.g. $(P \land Q) \lor R$

Logical Connectives

- Conjunction $\wedge$
  - Binary op., e.g. $P \wedge Q$, "P and Q", where P, Q are the *conjuncts*
- Disjunction $\vee$
  - Binary op., e.g. $P \vee Q$, "P or Q", where P, Q are the *disjuncts*
- Implication $\Rightarrow$
  - Binary op., e.g. $P \Rightarrow Q$, "P implies Q", where P is the *premise* (antecedent) and Q the *conclusion* (consequent)
  - Conditionals, "if-then" statements, or *rules*
- Equivalence $\Leftrightarrow$
  - Binary op., e.g. $P \Leftrightarrow Q$, "P equivalent to Q"
  - Biconditionals.
- Negation $\neg$
  - Unary op., e.g. $\neg P$, "not P"

Syntax of Propositional Logic
(Backus-Naur Form)

Sentence	$\rightarrow$	AtomicSentence | ComplexSentence
AtomicSentence	$\rightarrow$	LogicalConstant | PropositionalSymbol
ComplexSentence	$\rightarrow$	(Sentence) | Sentence LogicalConnective Sentence | ¬Sentence
LogicalConstant	$\rightarrow$	TRUE | FALSE
PropositionalSymbol	$\rightarrow$	P | Q | R | …
LogicalConnective	$\rightarrow$	$\wedge$ | $\vee$ | $\Leftrightarrow$ | $\Rightarrow$ | $\neg$

Precedence (from highest to lowest): $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$

e.g.: $\neg P \wedge Q \vee R \Rightarrow S$ (not ambiguous), eq. to: $(((\neg P) \wedge Q) \vee R) \Rightarrow S$

Semantics of Propositional Logic

- **Interpretation of symbols**
  - Logical constants have fixed meaning
    - True: always means the fact is the case; valid
    - False: always means the fact is not the case; unsatisfiable
  - Propositional symbols mean “whatever they mean”
    - e.g.: **P** “we are in a pit”, etc.
    - Satisfiable, but not valid (true only when the fact is the case)
- **Interpretation of sentences**
  - Meaning derived from the meaning of its parts
    - Sentence as a combination of sentences using connectives
  - Logical connectives as (boolean) functions:

    TruthValue ***f*** (TruthValue, TruthValue)

Semantics of Propositional Logic

- **Interpretation of connectives**
  - Truth-table
    - Define a mapping from input to output

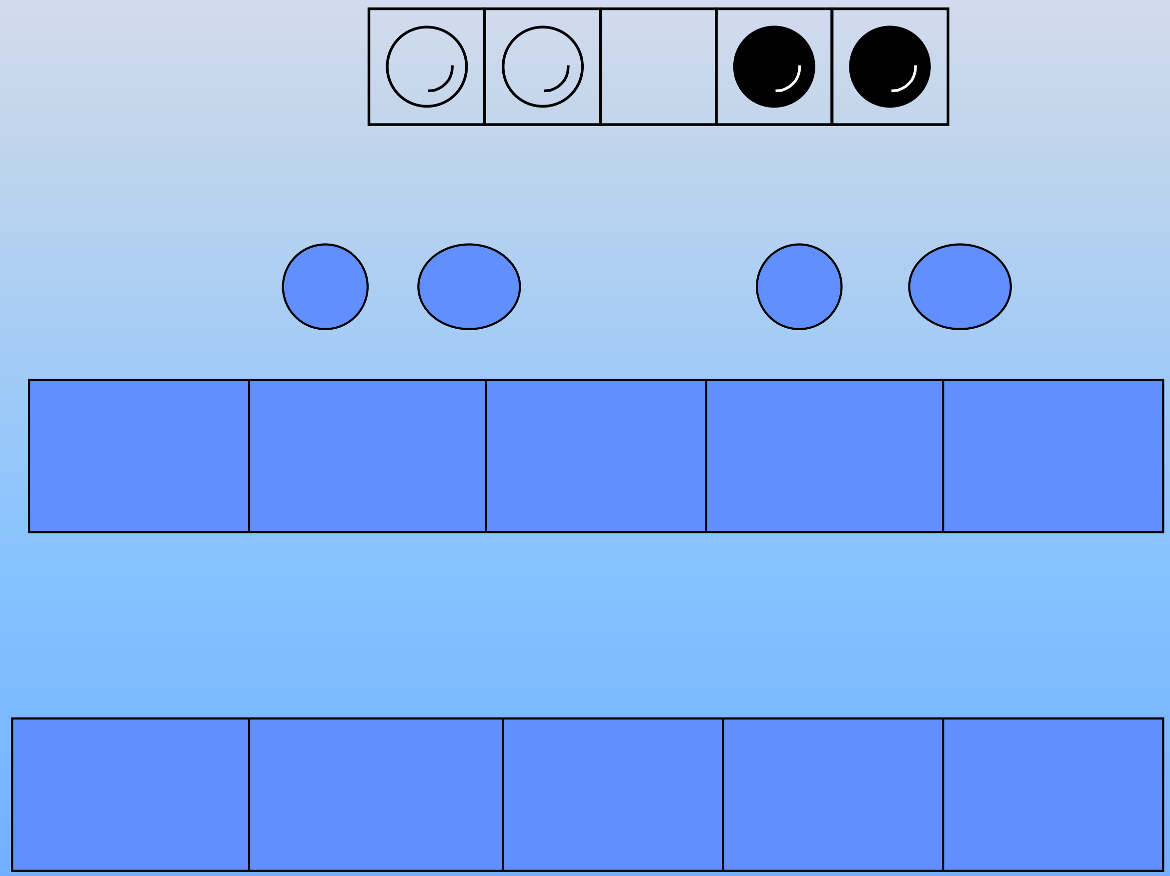
P	Q	¬ P	P ∧ Q	P ∨ Q	P ⇒ Q	P ⇔ Q
False	False	True	False	False	True	True
False	True	True	False	True	True	False
True	False	False	False	True	False	False
True	True	False	True	True	True	True

  - Interpretation of sentences by decomposition
    - e.g.: $\neg P \land Q \lor R \Rightarrow S$, with $P \leftarrow T, Q \leftarrow T, R \leftarrow F, S \leftarrow F$:

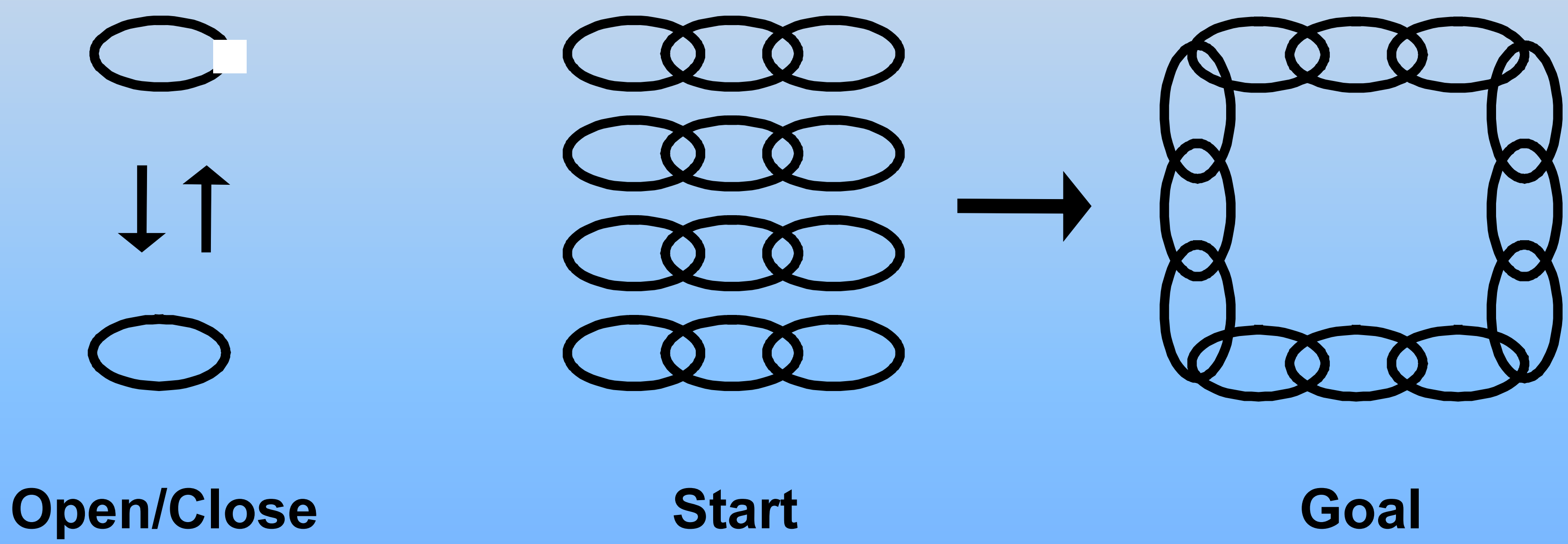
$\neg P \leftarrow F$ $\quad$ $((\neg P) \land Q) \lor R) \leftarrow F$

$(\neg P) \land Q \leftarrow F$ $\quad$ $(((\neg P) \land Q) \lor R) \Rightarrow S \leftarrow T$

Well-defined formulation of the stone puzzle:



Formulation of the chain problem:



Representation

- (k, l, c) ,   k>1

Permissible representation

- init: (O O – X X) – array W (pointer)
- Operations are if-than rules (mask to check for matching antecedent)
- ops:
  - MR: (O –) → (– O)
  - JR: (O X –) → (– X O)
  - ML: (– X) → (X –)
  - JL: (– O X) → (X O –)

< Back

Moorse Code

[<back](#)

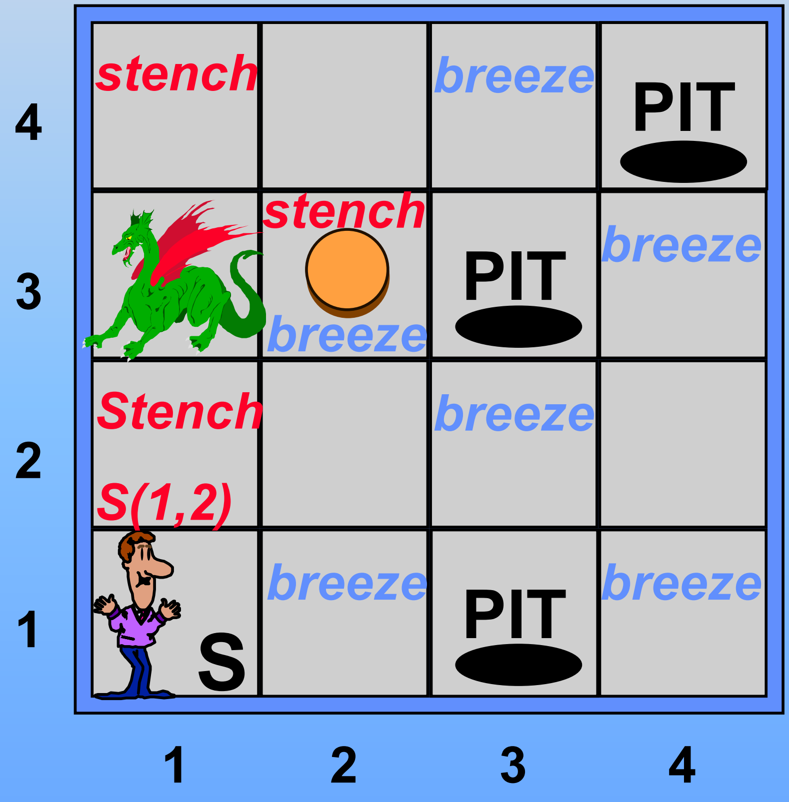
International Morse Code

1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

A	● ▬	U	● ● ▬
B	▬ ● ● ●	V	● ● ● ▬
C	▬ ● ▬ ●	W	● ▬ ▬
D	▬ ● ●	X	▬ ● ● ▬
E	●	Y	▬ ● ▬ ▬
F	● ● ▬ ●	Z	▬ ▬ ● ●
G	▬ ▬ ●		
H	● ● ● ●		
I	● ●		
J	● ▬ ▬ ▬		
K	▬ ● ▬	1	● ▬ ▬ ▬ ▬
L	● ▬ ● ●	2	● ● ▬ ▬ ▬
M	▬ ▬	3	● ● ● ▬ ▬
N	▬ ●	4	● ● ● ● ▬
O	▬ ▬ ▬	5	● ● ● ● ●
P	● ▬ ▬ ●	6	▬ ● ● ● ●
Q	▬ ▬ ● ▬	7	▬ ▬ ● ● ●
R	● ▬ ●	8	▬ ▬ ▬ ● ●
S	● ● ●	9	▬ ▬ ▬ ▬ ●
T	▬	0	▬ ▬ ▬ ▬ ▬

Wumpus World

< Back



Fuzzy Rules <Back

Fuzzy Rules generated by learning using a hippocampal like fuzzy neural learning network implementing a sound inference based on Compositional Rule Inference.

Condition				Consequence			Derived rule	Condition				Consequence			Derived rule	Condition				Consequence			Derived rule
1	2	3	4	SE	VE	VI		1	2	3	4	SE	VE	VI		1	2	3	4	SE	VE	VI	
S	S	S	S	19.05	0	0	SE	S	S	S	M	0	0	0	Deleted	S	S	S	L	0	0	0	Deleted
M	S	S	S	6.285	0	0	SE	M	S	S	M	0	0	0	Deleted	M	S	S	L	0	0	0	Deleted
L	S	S	S	4.075	0	0	SE	L	S	S	M	0	0	0	Deleted	L	S	S	L	0	0	0	Deleted
S	M	S	S	7.198	0	0	SE	S	M	S	M	0	0	0	Deleted	S	M	S	L	0	0	0	Deleted
M	M	S	S	0.451	0	0	SE	M	M	S	M	0	0	0	Deleted	M	M	S	L	0	0	0	Deleted
L	M	S	S	0.28	0	0	SE	L	M	S	M	0	0	0	Deleted	L	M	S	L	0	0	0	Deleted
S	L	S	S	17.95	0	0	SE	S	L	S	M	0	0	0	Deleted	S	L	S	L	0	0	0	Deleted
M	L	S	S	4.334	0	0	SE	M	L	S	M	0	0	0	Deleted	M	L	S	L	0	0	0	Deleted
L	L	S	S	2.498	0	0	SE	L	L	S	M	0	0	0	Deleted	L	L	S	L	0	0	0	Deleted
S	S	M	S	0	0	0	Deleted	S	S	M	M	0	4.21	0.224	VE	S	S	M	L	0	0.444	0.85	VI
M	S	M	S	0	0	0	Deleted	M	S	M	M	0	18.4	0	VE	M	S	M	L	0	2.841	1.793	VE
L	S	M	S	0	0	0	Deleted	L	S	M	M	0	17.19	0	VE	L	S	M	L	0	2.688	1.793	VE
S	M	M	S	0	0	0	Deleted	S	M	M	M	0	4.529	0.224	VE	S	M	M	L	0	0.444	0.85	VI
M	M	M	S	0	0	0	Deleted	M	M	M	M	0	18.69	0.128	VE	M	M	M	L	0	2.488	1.921	VE
L	M	M	S	0	0	0	Deleted	L	M	M	M	0	17.48	0.128	VE	L	M	M	L	0	2.53	1.921	VE
S	L	M	S	0	0	0	Deleted	S	L	M	M	0	3.69	0.224	VE	S	L	M	L	0	0.444	0.843	VI
M	L	M	S	0	0	0	Deleted	M	L	M	M	0	18.11	0	VE	M	L	M	L	0	2.841	1.793	VE
L	L	M	S	0	0	0	Deleted	L	L	M	M	0	18.15	0	VE	L	L	M	L	0	2.688	1.793	VE
S	S	L	S	0	0	0	Deleted	S	S	L	M	0	0	0	Deleted	S	S	L	L	0	0	0.401	VI
M	S	L	S	0	0	0	Deleted	M	S	L	M	0	2.398	1.452	VE	M	S	L	L	0	1.623	13.38	VI
L	S	L	S	0	0	0	Deleted	L	S	L	M	0	2.901	1.629	VE	L	S	L	L	0	1.798	20.55	VI
S	M	L	S	0	0	0	Deleted	S	M	L	M	0	0	0	Deleted	S	M	L	L	0	0	0.401	VI
M	M	L	S	0	0	0	Deleted	M	M	L	M	0	2.398	1.41	VE	M	M	L	L	0	1.623	12.79	VI
L	M	L	S	0	0	0	Deleted	L	M	L	M	0	2.901	1.842	VE	L	M	L	L	0	1.798	19.28	VI
S	L	L	S	0	0	0	Deleted	S	L	L	M	0	0	0	Deleted	S	L	L	L	0	0	0.401	VI
M	L	L	S	0	0	0	Deleted	M	L	L	M	0	2.288	0.881	VE	M	L	L	L	0	1.623	12.08	VI
L	L	L	S	0	0	0	Deleted	L	L	L	M	0	2.771	1.309	VE	L	L	L	L	0	1.798	18.43	VI

end

Part III – Knowledge and Reasoning

- **6 Agents that Reason Logically**
  - Knowledge-based Agents. – Representations.
  - Propositional Logic. – The Wumpus World.
- **7 First-Order Logic**
  - Syntax and Semantics. – Using First-Order Logic.
  - Logical Agents. – Representing Changes.
  - Deducing Properties of the World.
  - Goal-based Agents.
- **8 Building a Knowledge Base**
  - Knowledge Engineering. – General Ontology.

Validity and Inference

- **Testing for validity**
  – Using truth-tables, checking all possible configurations
    - e.g.: $((P \vee Q) \wedge \neg Q) \Rightarrow P$

P	Q	$P \vee Q$	$\neg Q$	$(P \vee Q) \wedge \neg Q$	$((P \vee Q) \wedge \neg Q) \Rightarrow P$
False	False	False	True	False	True
False	True	True	False	False	True
True	False	True	True	True	True
True	True	True	False	False	True

- **A method for sound inference**
  – Build and check a truth-table for *Premises* $\Rightarrow$ *Conclusion*

Rules of Inference

- **Sound inference rules**
  - Pattern of inference, that occur again and again
  - Soundness proven once and for all (truth-table)

$$\frac{\alpha}{\beta}$$

- **Classic rules of inference**
  - Implication-Elimination, or *Modus Ponens*
    - $$\frac{\alpha \Rightarrow \beta,\ \alpha}{\beta}$$

      e.g. Cloudy Λ Humid $\Rightarrow$ Rain
      Cloudy Λ Humid $\models$ Rain

Rules of Inference

- **Classic rules of inference**
  - And-Elimination
    - $$\frac{\alpha_1 \land \alpha_2 \land \ldots \land \alpha_n}{\alpha_i}$$

    e.g. Cloudy $\land$ Humid $\models$ Cloudy
    Cloudy $\Rightarrow$ NoSunTan
  - And-Introduction
    - $$\frac{\alpha_1, \alpha_2, \ldots, \alpha_n}{\alpha_1 \land \alpha_2 \land \ldots \land \alpha_n}$$

    e.g. Cloudy, Humid
    Cloudy $\land$ Humid $\Rightarrow$ Rain
  - Or-Introduction
    - $$\frac{\alpha_i}{\alpha_1 \lor \alpha_2 \lor \ldots \lor \alpha_n}$$
  - Double-Negation-Elimination
    - $$\frac{\neg\neg\alpha}{\alpha}$$

Rules of Inference

- **The resolution rule of inference**
  - Unit Resolution
    - $$\frac{\alpha \vee \beta, \quad \neg\beta}{\alpha}$$
  - Resolution
    - $$\frac{\alpha \vee \beta, \quad \neg\beta \vee \gamma}{\alpha \vee \gamma}$$

same as MP: $\frac{P \Rightarrow Q, \; P}{Q}$ i.e. $\frac{\neg\beta \Rightarrow \alpha, \quad \neg\beta}{\alpha}$

e.g. monday $\vee$ tuesday, $\neg$ monday |= tuesday

Truth-table for the resolution

α	β	γ	$\alpha \vee \beta$	$\neg\beta \vee \gamma$	$\alpha \vee \gamma$
False	False	False	False	True	False
False	False	True	False	True	True
False	True	False	True	False	False
False	True	True	True	True	True
True	False	False	True	True	True
True	False	True	True	True	True
True	True	False	True	False	True
True	True	True	True	True	True

Implication rewrite rule

Equivalence Rules

- **Inference as implication**
  - Equivalent notations, e.g. MP:
    - $\dfrac{\alpha \Rightarrow \beta, \alpha}{\beta}$ $\qquad \alpha \Rightarrow \beta, \beta \vdash \beta$ $\qquad ((\alpha \Rightarrow \beta) \land \alpha) \Rightarrow \beta$

      $\alpha \Rightarrow \beta, \beta \models \beta$

- **Equivalence rules**
  - Associativity: $\alpha \land (\beta \land \gamma) \Leftrightarrow (\alpha \land \beta) \land \gamma$

    $\alpha \lor (\beta \lor \gamma) \Leftrightarrow (\alpha \lor \beta) \lor \gamma$
  - Distributivity: $\alpha \land (\beta \lor \gamma) \Leftrightarrow (\alpha \land \beta) \lor (\alpha \land \gamma)$

    $\alpha \lor (\beta \land \gamma) \Leftrightarrow (\alpha \lor \beta) \land (\alpha \lor \gamma)$
  - De Morgan's Law: $\neg(\alpha \lor \beta) \Leftrightarrow \neg\alpha \land \neg\beta$

    $\neg(\alpha \land \beta) \Leftrightarrow \neg\alpha \lor \neg\beta$

Complexity of Inference

- **Proof by truth-table**
  - Complete
    - The truth-table can always be written.
  - Exponential time complexity
    - A proof involving ***N*** proposition symbols requires $\mathbf{2^N}$ rows.
    - In practice, a proof may refer only to a small subset of the KB.
- **Monotonicity**
  - Knowledge always increases

    if $KB_1 \models \alpha$ **then** $(KB_1 \cup KB_2) \models \alpha$

    - Allows for <u>local</u> rules,
      e.g. Modus Ponens $\alpha \Rightarrow \beta, \alpha \vdash \beta$
    - Propositional and first-order logic are monotonic.

    What is an issue with a monotonically increasing knowledge base?

Horn Sentences

- **A particular sub-class of sentences**
  - Implication: $\mathbf{P_1 \wedge P_2 \wedge \ldots \wedge P_N \Rightarrow Q}$ where $P_1, \ldots P_N$, Q are non-negated atoms.
  - Particular cases:
    - $Q \Leftrightarrow (\text{True} \Rightarrow Q)$
    - $(P_1 \vee P_2 \vee \ldots \vee P_N \Rightarrow Q) \Leftrightarrow (P_1 \Rightarrow Q) \wedge \ldots \wedge (P_N \Rightarrow Q)$
    - $(P \Rightarrow Q_1 \wedge \ldots \wedge Q_N) \Leftrightarrow (P \Rightarrow Q_1) \wedge \ldots \wedge (P \Rightarrow Q_N)$
    - $(P \Rightarrow Q_1 \vee \ldots \vee Q_N)$ cannot be represented
- **Prolog, a logic programming language**
  - Horn sentences + Modus-Ponens $\quad$ **Q :– $\mathbf{P_1}$, $\mathbf{P_2}$, … , $\mathbf{P_N}$**
  - Inference of <u>polynomial</u> time complexity

Part III – Knowledge and Reasoning

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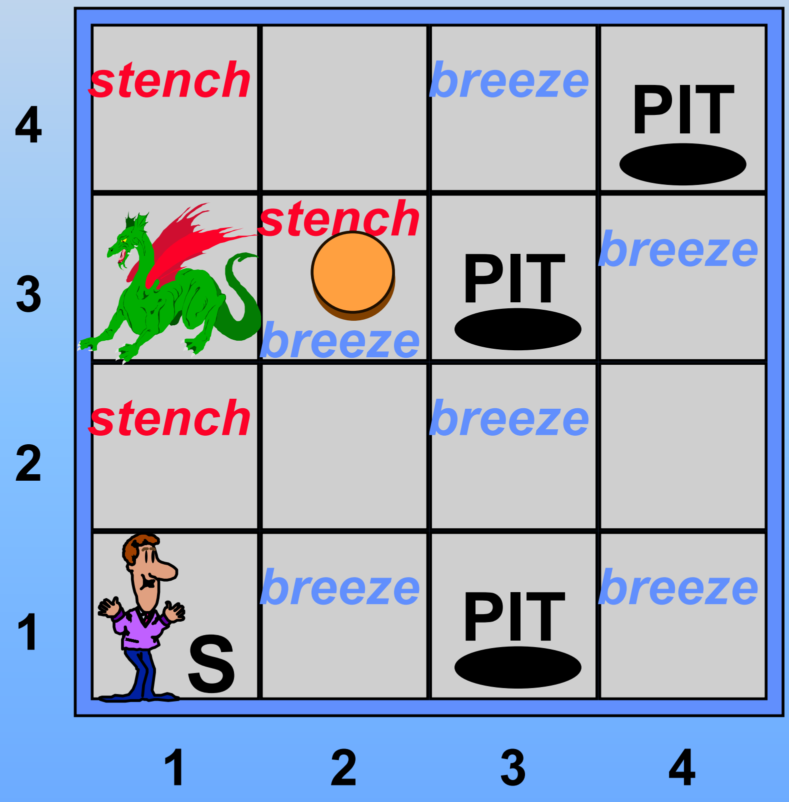
An Agent for the Wumpus World

- **A reasoning agent**
  - – Propositional logic as the "programming language"
  - – Knowledge base (KB) as problem representation
    - Percepts
    - Knowledge
    - Actions

    – sentences
  - – Rule of inference (e.g. Modus Ponens) as the algorithm that will find a solution

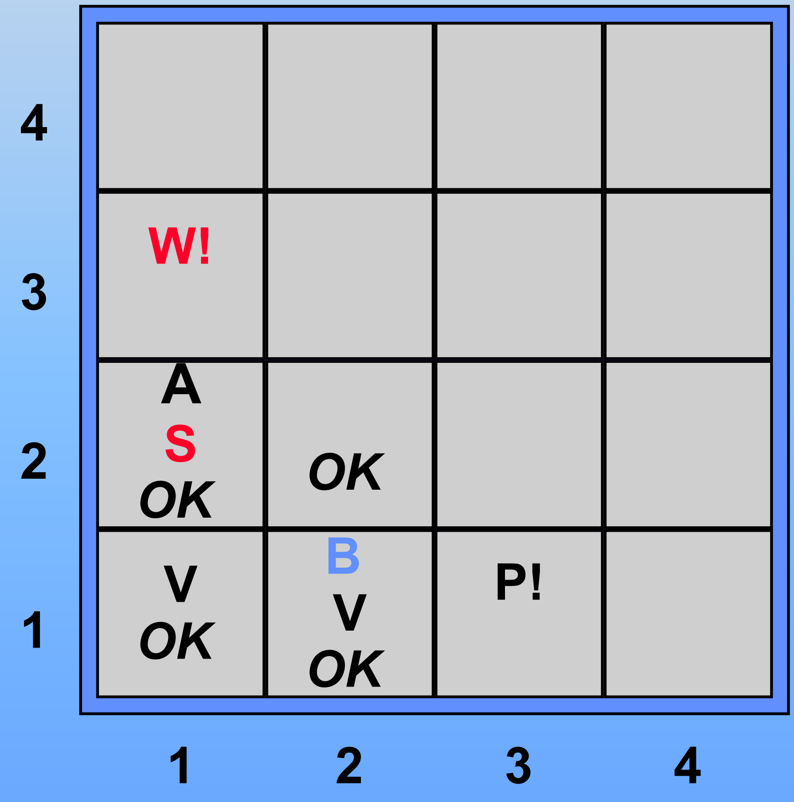


The Knowledge Base

- **TELLing the KB: percepts**
  - Syntax and semantics
    - Symbol **S11**, meaning "there is a stench at [1,1]"
    - Symbol **B12**, meaning "there is a breeze at [1,2]"

    …
- **Percept sentences**
  - Partial list:
    - ¬ S11, ¬ B11, ¬ G11, …
      ¬ S21, B21, ¬ G21, …
      S12, ¬ B12, ¬ G11, …
      …

[Stench , nil, nil, nil, nil]



The Knowledge Base

- **TELLing the KB: knowledge**
  - Rules about the environment
    - "All squares adjacent to the wumpus have a stench."
      $S12 \Rightarrow W11 \vee W12 \vee W22 \vee W13$
    - "A square with no stench has no wumpus and adjacent squares have no wumpus either."
      $\neg S11 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W12$
      $\neg S21 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W22 \wedge \neg W31$
      $\neg S12 \Rightarrow \neg W11 \wedge \neg W12 \wedge \neg W22 \wedge \neg W13$

[Stench , nil, nil, nil, nil]

	1	2	3	4
4				
3	W!			
2	A S OK	OK		
1	V OK	B V OK	P!	

Finding the Wumpus

- **Checking the truth-table**
  - Exhaustive check: every row for which KB is true also has W13 true
    - 12 propositional symbols, i.e. S11, S21, S12, W11, W21, W12, W22, W13, W31, B11, B21, B12
    - $2^{12} = 4096$ rows
  - > *possible, but lengthy*   *impossible for the complete problem*

KB $\Rightarrow$ W13

- **Reasoning by inference**
  - Application of a sequence of inference rules (proof)
    - Modus Ponens, And-Elimination, and Unit-Resolution

Proof for "KB $\Rightarrow$ W13"

Knowledge Base

$\neg S11$, $\neg B11$, $\neg G11$,
$\neg S21$, $B21$, $\neg G21$,
$S12$, $\neg B12$, $\neg G11$,

R1: $\neg S11 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W12$

R2: $\neg S21 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W22 \wedge \neg W31$

R3: $\neg S12 \Rightarrow \neg W11 \wedge \neg W12 \wedge \neg W22 \wedge \neg W13$

R4: $S12 \Rightarrow W11 \vee W12 \vee W22 \vee W13$

Inferences

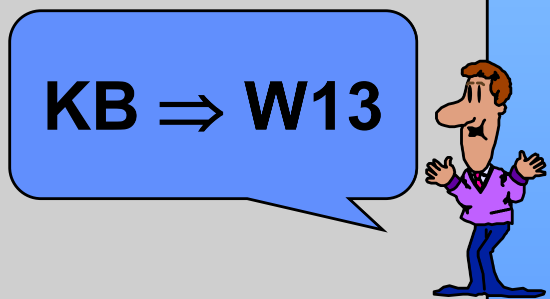
1. Modus Ponens: $\neg S11$, **R1**
   $\vdash \neg W11 \wedge \neg W21 \wedge \neg W12$
2. And-Elimination: ♦
   $\vdash \neg W11,\ \neg W21,\ \neg W12$
3. Modus Ponens: $\neg S21$, **R2**
   $\vdash \neg W11 \wedge \neg W21 \wedge \neg W22 \wedge \neg W31$
4. And-Elimination: ♦
   $\vdash \neg W11, \neg W21, \neg W22,\ \neg W31$

Proof for "KB ⇒ W13"

Knowledge Base	Inferences
$\neg S11$, $\neg B11$, $\neg G11$, $\neg S21$, $B21$, $\neg G21$, $S12$, $\neg B12$, $\neg G11$, **R1:** $\neg S11 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W12$ **R2:** $\neg S21 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W22 \wedge \neg W31$ **R3:** $\neg S12 \Rightarrow \neg W11 \wedge \neg W12 \wedge \neg W22 \wedge \neg W13$ **R4:** $S12 \Rightarrow W11 \vee W12 \vee W22 \vee W13$	KB += $\neg W11$, $\neg W21$, $\neg W12$, $\neg W22$, $\neg W31$ 5. Modus Ponens: S12, **R4** $\vdash$ $(W13 \vee W12 \vee W22) \vee W11$ 6. Unit-Resolution: ♦, $\neg W11$ $\vdash$ $(W13 \vee W12) \vee W22$

Proof for "KB ⇒ W13"

Knowledge Base	Inferences
$\neg S11$, $\neg B11$, $\neg G11$, $\neg S21$, $B21$, $\neg G21$, $S12$, $\neg B12$, $\neg G11$, **R1:** $\neg S11 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W12$ **R2:** $\neg S21 \Rightarrow \neg W11 \wedge \neg W21 \wedge \neg W22 \wedge \neg W31$ **R3:** $\neg S12 \Rightarrow \neg W11 \wedge \neg W12 \wedge \neg W22 \wedge \neg W13$ **R4:** $S12 \Rightarrow W11 \vee W12 \vee W22 \vee W13$	KB += $\neg W11$, $\neg W21$, $\neg W12$, $\neg W22$, $\neg W31$, $(W13 \vee W12) \vee W22$ 7. Unit-Resolution: ♦, $\neg W22$ $\vdash$ $W13 \vee W12$ 8. Unit-Resolution: ♦, $\neg W12$ $\vdash$ $W13$



From Knowledge to Actions

- **TELLing the KB: actions**
  - Additional rules
    - e.g. “if the wumpus is 1 square ahead then do not go forward”

      $A12 \wedge East \wedge W22 \Rightarrow \neg Forward$

      $A12 \wedge North \wedge W13 \Rightarrow \neg Forward$

      ...
- **ASKing the KB**
  - Cannot ask “which action?” but “should I go forward?”

[Stench , nil, nil, nil, nil]

4				
3	W!			
2	A S OK	OK		
1	V OK	B V OK	P!	
	1	2	3	4

The Limits of Propositional Logic

- **A weak logic**
  - Too many propositions to TELL the KB
    - e.g. the rule "if the wumpus is 1 square ahead then do not go forward" needs 64 sentences (16 squares x 4 orientations)!
    - Result in increased time complexity of inference
  - Handling change is difficult
    - Need time-dependent propositional symbols
      e.g. A11 means "the agent is in square [1,1]" - when?
      at t = 0: A11-0; at t = 1: A21-1;
      at t = 2: A11-2
    - Need to rewrite rules as time-dependent
      e.g. $A12\text{-}0 \land East\text{-}0 \land W22\text{-}0 \Rightarrow \neg Forward\text{-}0$
      $A12\text{-}2 \land East\text{-}2 \land W22\text{-}2 \Rightarrow \neg Forward\text{-}2$

Summary

- **Intelligent agents need …**
  - Knowledge about the world, so as to take good decisions.
- **Knowledge can be …**
  - Defined using a knowledge representation language.
  - Stored in a knowledge base in the form of sentences.
  - Inferred, using an inference mechanism and rules.
- **A representation language is defined by …**
  - A syntax, which specify the structure of sentences, and
  - A semantics, which specifies how the sentences relate to facts in the world.

Summary

- **Inference is …**
  - The process of deducing new sentences from old ones.
  - Sound if it derives true conclusions from true premises.
  - Complete if it can derive all possible true conclusions.
- **Logics …**
  - Make different commitments about what the world is made of and what kind of beliefs we can have about facts.
  - Are useful for the commitments they *do not* make.
- **Propositional logic …**
  - Commits only to the existence of facts.
  - Has simple syntax and semantics and is therefore limited.

References

- Newell, A. (1982). The knowledge level. *Artificial Intelligence*, 18(1):82-127.
- Quine, W. V. (1960). *Word and Object*. MIT Press, Cambridge, Massachusetts.
- Rosenschein, S. J. (1985). Formal theories of knowledge in AI and robotics. *New Generation Computing*, 3(4):345-357.
- Tarski, A. (1956). *Logic, Semantics, Metamathematics: Papers from 1923 to 1938*. Oxford University Press, Oxford.

end

Announcements

Example Classes starts next week.
Download the worksheets from edventure – logbook (jotter book) for introduction to prolog

And assignment for knowledge based system

1 week after the lab session (5pm)

Software project lab for logbook/jotter book and assignment submission.