# ARTIFICIAL INTELLIGENCE

Scalab

Grupo de Inteligencia Artificial (Scalab)
Departamento de Informática

Universidad Carlos III de Madrid

# Contents

# Production systems

- Problems with traditional CS
  - fixed control flow
  - sequential execution
  - not adequate in dynamic environments
- Solution: data driven operations

# Components of a Rule-based System

- Facts set or working memory: domain knowledge at any given moment

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- Rules set: set of rules (productions)

  `if` A THEN B

  A: conditions of application

  B: actions on the working memory or outside world

# Components of a Rule-based System

- Facts set or working memory: domain knowledge at any given moment
- Rules set: set of rules (productions)

  `if` A THEN B

  A: conditions of application

  B: actions on the working memory or outside world
- Control strategy, rule interpreter, or inference engine: responsible for chaining the rules execution

# Control strategy

Facts: P, R
Rules: R1. `if` P `then` J
Rules: R2. `if` R `then` K,L
Rules: R3. `if` P and R `then` L
Rules: R4. `if` L `then` F

Which one does the system execute?

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Which one does the system execute?

Facts: P, R
Program: `if` P `then` J
Else `if` R `then` K,L
Else `if` P and R `then` L
Else `if` L `then` F

# Components

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  - can be represented using any type of representation paradigm: simple facts, objects, logic, ...

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  - no disjunction $\rightarrow$ $n$ rules
  - no if-then-else $\rightarrow$ two rules
  - no explicit reference on the action part of a rule to another rule (only through facts)
  - if then-part only adds: monotonic reasoning

# Components

- Facts:
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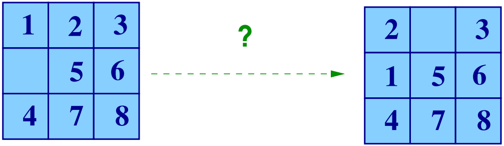
  - no explicit reference on the action part of a rule to another rule (only through facts)
  - if then-part only adds: monotonic reasoning
- Inference:
  - several cycles: at each cycle one (or more rules) are selected and applied
  - refraction: in most domains the same rule should not fire with the same values for its variables

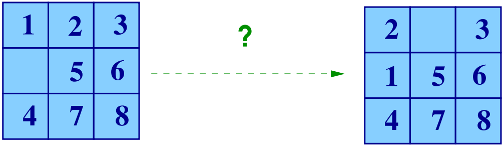
# Example: 8 puzzle. Working memory




- lists: (V11,V12,V13,...,V33)
- predicate logic: square(X,Y,Value)
- objects:

| Square | |
|---|---|
| `is-a:` | |
| **Attribute** | **Possible values/Value** |
| x | number [1..3] |
| y | number [1..3] |
| value | number [0..8] |

# 8-puzzle. Initial working memory

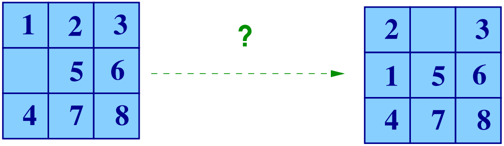



- lists: (1,2,3,0,5,6,4,7,8)
- predicate logic: square(1,1,1),square(2,1,2),. . . ,square(3,3,8)
- objects:

| **square11** | |
|---|---|
| `instance-of: Square` | |
| **Attribute** | **Possible values/Value** |
| x | 1 |
| y | 1 |
| value | 1 |

| **square21** | |
|---|---|
| `instance-of: Square` | |
| **Attribute** | **Possible values/Value** |
| x | 2 |
| y | 1 |
| value | 2 |

# 8-puzzle. Final working memory or goals




- lists: (2,0,3,1,5,6,4,7,8)
- predicate logic: square(1,1,2),square(2,1,0),. . . ,square(3,3,8)
- objects:

| **square11** | |
|---|---|
| `instance-of: Square` | |
| **Attribute** | **Possible values/Value** |
| x | 1 |
| y | 1 |
| value | 2 |

| **square21** | |
|---|---|
| `instance-of: Square` | |
| **Attribute** | **Possible values/Value** |
| x | 2 |
| y | 1 |
| value | 0 |

# 8-puzzle. Rule base

- lists

  If (0,X1,X2,X3,X4,X5,X6,X7,X8)
  Then (X1,0,X2,X3,X4,X5,X6,X7,X8)

  If (0,X1,X2,X3,X4,X5,X6,X7,X8)
  Then (X3,X1,X2,0,X4,X5,X6,X7,X8)

  ...
- Problem: involves identifying all the possible combinations of the empty position (0) and its possible moves

# 8-puzzle. Predicate logic

If square(X,Y,0),square(X1,Y,Z),X=X1+1
Then square(X1,Y,0),square(X,Y,Z),∼square(X,Y,0),∼square(X1,Y,Z)

If square(X,Y,0),square(X1,Y,Z),X=X1-1
Then square(X1,Y,0),square(X,Y,Z),∼square(X,Y,0),∼square(X1,Y,Z)

If square(X,Y,0),square(X,Y1,Z),Y=Y1+1
Then square(X,Y1,0),square(X,Y,Z),∼square(X,Y,0),∼square(X,Y1,Z)

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If square(X,Y,0),square(X,Y1,Z),Y=Y1+1
Then square(X,Y1,0),square(X,Y,Z),∼square(X,Y,0),∼square(X,Y1,Z)

If square(X,Y,0),square(X,Y1,Z),Y=Y1-1
Then square(X,Y1,0),square(X,Y,Z),∼square(X,Y,0),∼square(X,Y1,Z)

Alternative representation:

If on(x,y), free(z), adjacent(y,z)
Then on(x,z), free(y), ∼ on(x,y), ∼ free(z)

# 8-puzzle. Objects

| | |
|---|---|
| Up | If ?square ← (square (x ?x) (y ?y) (value 0))<br>?square1 ← (square (x ?x) (y ?y1) (value ?v))<br>(test ?y=?y1+1)<br>Then modifies(?square,value,?v),modifies(?square1,value,0) |
| Down | If ?square ← (square (x ?x) (y ?y) (value 0))<br>?square1 ← (square (x ?x) (y ?y1) (value ?v))<br>(test ?y=?y1-1)<br>Then modifies(?square,value,?v),modifies(?square1,value,0) |
| Right | If ?square ← (square (x ?x) (y ?y) (value 0))<br>?square1 ← (square (x ?x1) (y ?y) (value ?v))<br>(test ?x=?x1-1)<br>Then modifies(?square,value,?v),modifies(?square1,value,0) |
| Left | If ?square ← (square (x ?x) (y ?y) (value 0))<br>?square1 ← (square (x ?x1) (y ?y) (value ?v))<br>(test ?x=?x1+1)<br>Then modifies(?square,value,?v),modifies(?square1,value,0) |

# Operation of a PS

## Types of systems

- Forward chaining `if` P, then Q. P. Therefore, Q
- Backward chaining `if` P, then Q. $Q$?. $P$?

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## Phases

- Decision phase
  - Reduction (optional)
  - Matching: conflict set, RETE
  - Conflict set resolution
- Execution phase

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- Forward chaining `if` P, then Q. P. Therefore, Q
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## Phases

- Decision phase
  - Reduction (optional)
  - Matching: conflict set, RETE
  - Conflict set resolution
- Execution phase

## Termination

- Some specific fact (set of facts) is true (false)
- No more rules can be executed
- A given number of rules have been executed
- A halt signal is issued by a rule

# Matching

- First approach: computing and resolving the conflict set at each cycle
- Problem: slow

# Matching

- First approach: computing and resolving the conflict set at each cycle
- Problem: slow
- Solution: RETE algorithm (algorithm of temporary redundancy)
  - initially it establishes a graph from the rules (RETE network)
  - it propagates the contents of the initial facts base through the network
  - every time a change in the facts base arises (usually, through the consequent of a rule), the changes are propagated
  - at every cycle, a conflict set will be available at the end nodes of the network
- Key idea: structural similarity

# Forward chaining

Initial WM, $WM_0$: A, B, C

Rule set: R1. `if` A, B `then` D, E, not C

R2. `if` A `then` F, not B

R3. `if` C, B `then` G

R4. `if` E, F, G `then` H

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Matching:

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Matching: R1, R2, R3

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Initial WM, $WM_0$: A, B, C

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Matching: R1, R2, R3

Conflict Set Resolution (for example, first rule): R1

# Forward chaining

Initial WM, $WM_0$: A, B, C

Rule set: R1. `if` A, B `then` D, E, not C
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R4. `if` E, F, G `then` H

Matching: R1, R2, R3

Conflict Set Resolution (for example, first rule): R1

Execution: + D, E, - C
$WM_1$: A, B, D, E

# Forward chaining

Initial WM, $WM_0$: A, B, C

Rule set: R1. `if` A, B `then` D, E, not C
R2. `if` A `then` F, not B
R3. `if` C, B `then` G
R4. `if` E, F, G `then` H

Matching: R1, R2, R3

Conflict Set Resolution (for example, first rule): R1

Execution: + D, E, - C
$WM_1$: A, B, D, E

Matching: R1, R2

# Forward chaining

Initial WM, $WM_0$: A, B, C

Rule set: R1. `if` A, B `then` D, E, not C
R2. `if` A `then` F, not B
R3. `if` C, B `then` G
R4. `if` E, F, G `then` H

Matching: R1, R2, R3

Conflict Set Resolution (for example, first rule): R1

Execution: + D, E, - C
$WM_1$: A, B, D, E

Matching: R1, R2

Refraction: R1 cannot be used again. Conflict set: R2

# Forward chaining

Initial WM, $WM_0$: A, B, C
Rule set: R1. `if` A, B `then` D, E, not C
R2. `if` A `then` F, not B
R3. `if` C, B `then` G
R4. `if` E, F, G `then` H

Matching: R1, R2, R3

Conflict Set Resolution (for example, first rule): R1

Execution: + D, E, - C
$WM_1$: A, B, D, E

Matching: R1, R2

Refraction: R1 cannot be used again. Conflict set: R2

Conflict Set Resolution: R2
Execution: + F, - B
$WM_2$: A, D, E, F

# 8-puzzle. Objects

Up

If ?square ← (square (x ?x) (y ?y) (value 0))
?square1 ← (square (x ?x) (y ?y1) (value ?v))
(test ?y=?y1+1)
Then modifies(?square,value,?v),modifies(?square1,value,0)

Down

If ?square ← (square (x ?x) (y ?y) (value 0))
?square1 ← (square (x ?x) (y ?y1) (value ?v))
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Right

If ?square ← (square (x ?x) (y ?y) (value 0))
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(test ?x=?x1-1)
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Left

If ?square ← (square (x ?x) (y ?y) (value 0))
?square1 ← (square (x ?x1) (y ?y) (value ?v))
(test ?x=?x1+1)
Then modifies(?square,value,?v),modifies(?square1,value,0)

# Forward chaining

Initial WM: (square11 (x 1) (y 1) (value 1))
(square21 (x 2) (y 1) (value 2))
...
(square33 (x 3) (y 3) (value 8))

Matching:
(Up, ?x=1, ?y=2, ?y1=1, ?v=1, ?square=#square12, ?square1=#square11)
(Down, ?x=1, ?y=2, ?y1=3, ?v=4, ?square=#square12, ?square1=#square13)
(Right, ?x=1, ?y=2, ?x1=2, ?v=5, ?square=#square12, ?square1=#square22)

Resolution of the Conflict Set (for example, first rule):
(Up, ?x=1, ?y=2, ?y1=1, ?v=1, ?square=#square12, ?square1=#square11)

Execution: (- (square12 (x 1) (y 2) (value 0)))
(+ (square12 (x 1) (y 2) (value 1)))
(- (square11 (x 1) (y 1) (value 1)))
(+ (square11 (x 1) (y 1) (value 0)))

Matching ...

# Backward chaining

Initial WM, $WM_0$: A, B, C

Goals: H?

Rule set: R1. `if` A, B `then` D, E, not C

R2. `if` A `then` F, not B

R3. `if` C, B `then` G

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Matching:

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R4. `if` E, F, G `then` H

Matching: R4

# Backward chaining

Initial WM, $WM_0$: A, B, C
Goals: H?
Rule set: R1. `if` A, B `then` D, E, not C
R2. `if` A `then` F, not B
R3. `if` C, B `then` G
R4. `if` E, F, G `then` H

Matching: R4
Conflict Set Resolution: R4

# Backward chaining

Initial WM, $WM_0$: A, B, C

Goals: H?

Rule set: R1. `if` A, B `then` D, E, not C

R2. `if` A `then` F, not B

R3. `if` C, B `then` G

R4. `if` E, F, G `then` H

Matching: R4

Conflict Set Resolution: R4

Execution: + E?, F?, G?, - H?

Goals: E, F, G

# Backward chaining

Initial WM, $WM_0$: A, B, C
Goals: H?
Rule set: R1. `if` A, B `then` D, E, not C
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R4. `if` E, F, G `then` H

Matching: R4
Conflict Set Resolution: R4

Execution: + E?, F?, G?, - H?
Goals: E, F, G

Matching:

# Backward chaining

Initial WM, $WM_0$: A, B, C
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R4. `if` E, F, G `then` H

Matching: R4
Conflict Set Resolution: R4

Execution: + E?, F?, G?, - H?
Goals: E, F, G

Matching: R1, R2, R3

# Backward chaining

Initial WM, $WM_0$: A, B, C
Goals: H?
Rule set: R1. `if` A, B `then` D, E, not C
R2. `if` A `then` F, not B
R3. `if` C, B `then` G
R4. `if` E, F, G `then` H

Matching: R4
Conflict Set Resolution: R4

Execution: + E?, F?, G?, - H?
Goals: E, F, G

Matching: R1, R2, R3

Conflict Set Resolution (first rule): R1
Execution: + A?, B?
True in $WM_0$
If we execute now R1, $WM_1$: A, B, D, E
Goals: F, G

# Backward chaining (like PROLOG)

Goals: (square11 (value 2))
(square21 (value 0))
...
(square33 (value 8))

Reduction: goal selection (for example, the first)
(square11 (value 2))

Matching:
(Up, ?v=2, ?square=#square11)
(Down, ?v=2, ?square=#square11)
(Right, ?v=2, ?square=#square11)
(Left, ?v=2, ?square=#square11)

Resolution of Conflict Set (for example, first rule):
(Up, ?v=2, ?square=#square11)

# Backward chaining (like PROLOG)

Execution: introduce the conditions of the instantiated rule
on the set of goals

?square=#square11 and (?square $\leftarrow$ (square (x ?x) (y ?y) (value 0)))
then ?x=1, ?y=1
and adds goal (square11 (value 0))
?v=2 and (?square1 $\leftarrow$ (square (x ?x) (y ?y1) (value ?v)))
then (?square1 $\leftarrow$ (square (x 1) (y ?y1) (value 2)))
(test ?y=?y1+1), ?y=1 and (?square1 $\leftarrow$ (square (x 1) (y ?y1) (value 2)))
then ?square1=#square21 and ?y1=0!!!
and adds goal (square21 (value 2))

The list of goals is: (square11 (value 0))
(square21 (value 2))
(square21 (value 0))
...
(square33 (value 8))

Reduction: ...

# Redesign (backward chaining)

Up

If ?square $\leftarrow$ (square (x ?x) (y ?y) (value 0))
(test ?y>1)
?square1 $\leftarrow$ (square (x ?x) (y ?y1) (value ?v))
(test ?y=?y1+1)
Then modifies(?square,value,?v),modifies(?square1,value,0)

Down

If ?square $\leftarrow$ (square (x ?x) (y ?y) (value 0))
(test ?y<3)
?square1 $\leftarrow$ (square (x ?x) (y ?y1) (value ?v))
(test ?y=?y1-1)
Then modifies(?square,value,?v),modifies(?square1,value,0)

Right

If . . .
(test ?x<3)
Then modifies(?square,value,?v),modifies(?square1,value,0)

Left

If . . .
(test ?x>1)
Then modifies(?square,value,?v),modifies(?square1,value,0)

# Comparing chaining modes

- Disadvantages of forward chaining
  - does not focus on goals
  - initially all data should be in working memory
  - greater amount of comparisons
- Disadvantages of backward chaining
  - handling goals and subgoals is needed
  - actions that solve the problem are unknown until the very end
- Choosing one
  - number of initial and goal states
  - branching factor
  - justifications needed

# Strategy characteristics

- The most general possible
- The most efficient possible (heuristics): implicit or explicit
- Change state
- Be systematic

# Resolution strategies

- First rule
- More knowledge
- Greater priority
- More specific
- More general
- Considering the newest element
- No prior execution
- More executions
- Randomly
- Explore all
- Meta rules
- Mixed strategies

# Advantages of production systems

- It is natural for experts to express knowledge as rules

  *If patient has fever and sneezes*
  *then diagnosis is flu*

- There is already a formal analysis of rule-based knowledge (as in logic)
- If rules apply, they generate new knowledge, so that new rules can fire

  *If patient has flu*
  *then treatment is stay at home*

- A set of rules can be easily mantained by adding or removing rules

# Advantages and disadvantages

- Advantages
  - modularity, which facilitates incremental growth
  - declarative character
  - uniformity
  - naturalness
  - flexibility
  - learning
  - modeling of animal and human behavior
- Disadvantages
  - inefficient
  - opacity
  - difficult to represent algorithms

# Going to the real world

## Applications

- Expert systems: medicine, oil discovery, computers configuration, risks analysis, ...
- Microsoft problem solving
- Business rules
- Laws, vaccination, telecommunications
- Control
- Games

## Tools

- Academic: OPS V, Frulekit
- Professional: Web Sphere (IBM), Business rules (Oracle), CLIPS/JESS (NASA)
- Others: RuleML (`http://www.ruleml.org/`), Prolog

# Prolog

- Declarative programming language
- Based on predicate logic
- Example:

```
number-accesses(johnsmith,15).
number-accesses(anntaylor,34).
total-spent(johnsmith,300).
total-spent(anntaylor,50).
good-client(X) :- often-access(X), medium-expenses(X).
good-client(X) :- medium-access(X), high-expenses(X).
low-access(X) :- number-accesses(X,Y), Y < 10.
medium-access(X) :- number-accesses(X,Y), Y >= 10, Y < 30.
often-access(X) :- number-accesses(X,Y), Y >= 30.
low-expenses(X) :- total-spent(X,Y), Y < 100.
medium-expenses(X) :- total-spent(X,Y), Y >= 100, Y < 300.
high-expenses(X) :- total-spent(X,Y), Y >= 300.
```

# Example in *Age of Empires*

```
// Rule to sell excess resources
(defrule
    (wood-amount > 1200)
    (or (food-amount < 1600)
        (or (gold-amount < 1200)
            (stone-amount < 650)))
    (can-sell-commodity wood)
    =>
    (chat-local-to-self “excess wood”)
    (release-escrow wood)
    (sell-commodity wood))
```