CS 4700:
Foundations of Artificial Intelligence

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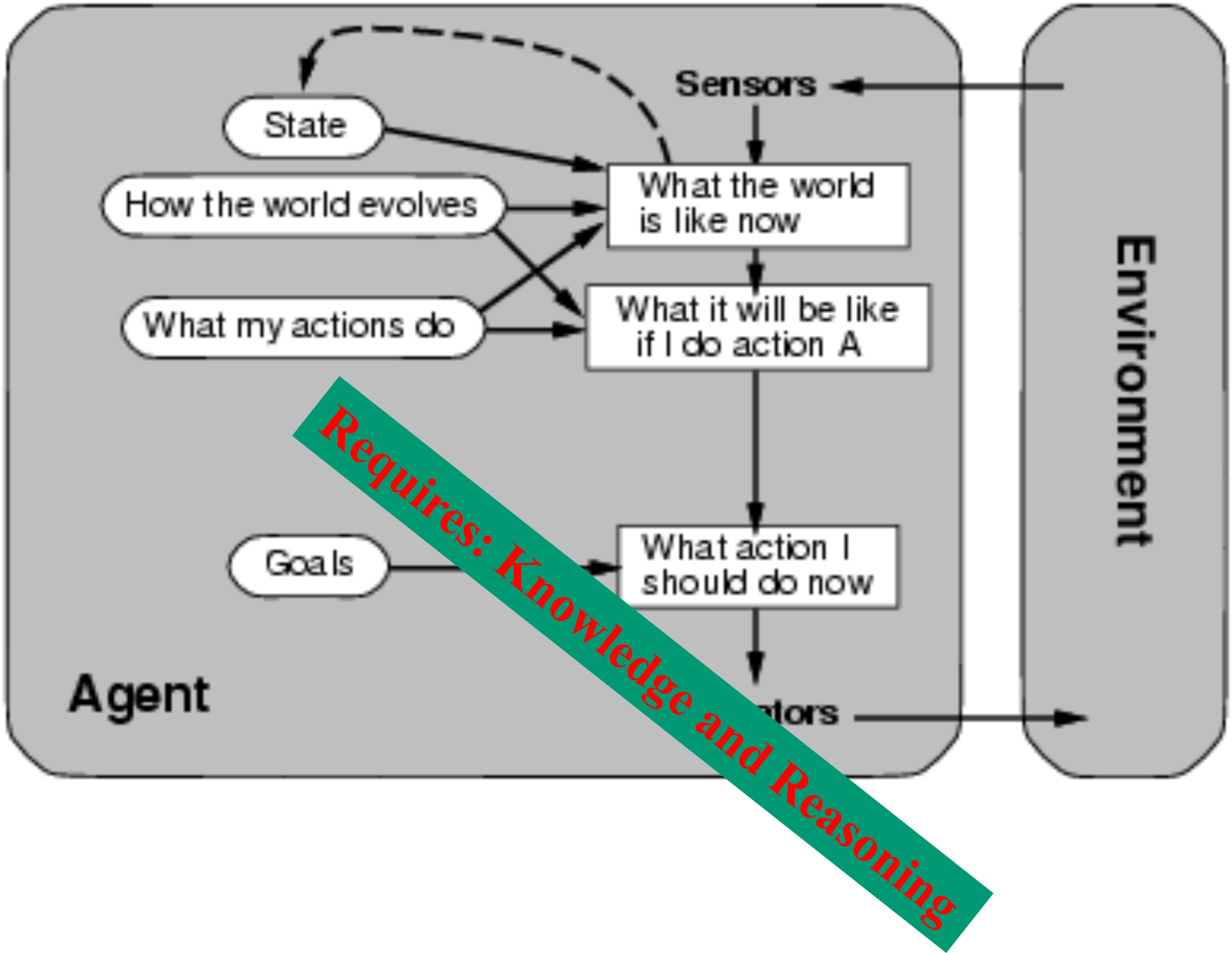
Logical Agents ---
Intro Knowledge Representation
& Boolean Satisfiability (SAT) encodings

R&N: Chapter 7

A Model-Based Agent



Knowledge and Reasoning

Knowledge and Reasoning:

humans are very good at acquiring new information by combining raw knowledge, experience with reasoning.

AI-slogan: "Knowledge is power" (or "Data is power"?)

Examples:

Medical diagnosis --- physician diagnosing a patient infers what disease, based on the knowledge he/she acquired as a student, textbooks, prior cases

Common sense knowledge / reasoning --- common everyday assumptions / inferences. e.g.,

(1) "lecture starts at four" infer pm not am;

(2) when traveling, I assume there is some way to get from the airport to the hotel.

Logical agents:

Agents with some representation of the complex knowledge about the world / its environment, and uses inference to derive new information from that knowledge combined with new inputs (e.g. via perception).

Key issues:

1- Representation of knowledge
What form? Meaning / semantics?

2- Reasoning and inference processes
Efficiency.

Knowledge-base Agents

Key issues:

- Representation of knowledge → knowledge base
- Reasoning processes → inference/reasoning

Knowledge base = set of sentences in a formal language representing facts about the world (*)

(*) called Knowledge Representation (KR) language

Knowledge Representation language candidate:
logical language (propositional / first-order)
combined with a logical inference mechanism

Why not use natural language (e.g. English)?

We want clear syntax & semantics (well-defined meaning), and, mechanism to infer new information.
Soln.: Use a formal language.

More Concrete: Propositional Logic

Syntax: build sentences from atomic propositions, using connectives $\wedge, \vee, \neg, \Rightarrow, \Leftrightarrow$.
(and / or / not / implies / equivalence (biconditional))

E.g.: $((\neg P) \vee (Q \wedge R)) \Rightarrow S$

Note: You have seen propositional logic in other courses. Make sure you review!

Semantics

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

Note: $\Rightarrow$ somewhat counterintuitive.

What's the truth value of "5 is even implies Sam is smart"?

True!

Boolean Satisfiability (SAT

9

Propositional Satisfiability problem

Satifiability (SAT): Given a formula in propositional calculus, is there a model (i.e., a satisfying interpretation, an assignment to its variables) making it true?

We consider clausal form, e.g.:

$$(a \vee \neg b \vee \neg c) \text{ AND } (b \vee \neg c) \text{ AND } (a \vee c)$$

2^n possible assignments

Note: Any propositional logic expression can be rewritten in clausal form.

SAT: prototypical hard combinatorial search and reasoning problem.
Problem is NP-Complete. (Cook 1971)
Surprising "power" of SAT for encoding computational problems
Modern SAT Solvers use this language.

SAT Encodings

We'll use clausal form to encode our task specific knowledge in such way that a satisfying assignment to the Boolean variables represents a solution the the task under consideration.

A broad range of (AI) reasoning tasks can be encoded this way. E.g., planning, scheduling, diagnosis, and verification.

SAT Solvers

Modern Satisfiability (SAT) solvers operating on the clausal form are surprisingly *much* more efficient than other logic-based approaches (e.g., pure resolution that will be discussed later)

The SAT solvers treat the set of clauses as a set of constraints (disjunctions) on Boolean variables. Current solvers are very powerful. Can handle 1 Million+ variables and several millions of clauses.

Systematic: Davis Putnam (DPLL) + *series of improvements*
Stochastic local search: WalkSAT (issue?)

Satisfiability as an Encoding Language

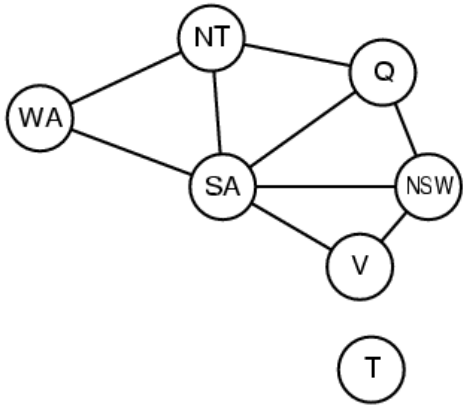
SAT Translation of Graph Coloring

Variables

NxK vars

$C_{i,k}$ node i has color k

Total # colors: K. Total # nodes: N.



At least one of K colors per node i :

$(C_{i,1} \vee C_{i,2} \vee C_{i,3} \vee \ldots \vee C_{i,K})$

At most one color per node i :

$(\sim C_{i,k} \vee \sim C_{i,k'})$ for all k =/= k'

If node i and node j (=/= i) share an edge, need to have different colors:

$(\sim C_{i,l} \vee \sim C_{j,l})$ for all 1 <= l <= K

Note: Translation from "problem" into SAT. Reverse of usual translation to show NP-completeness.

Works also for (easy) polytime problems!

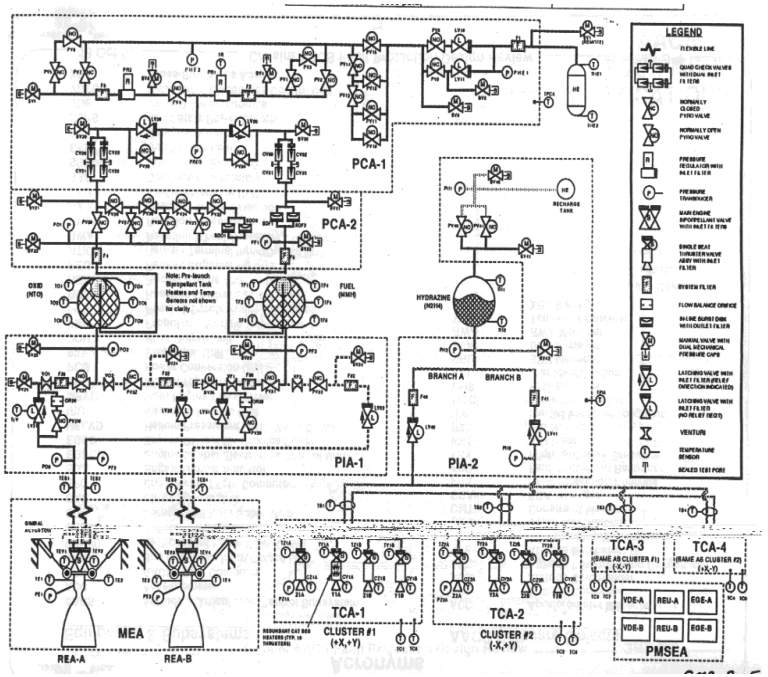
SAT Solvers in the Real World

NASA Deep Space One Spacecraft: Remote Agent

- Remote Agent (remote intelligent self-repair software) (RAX), developed at NASA and JPL, was the first artificial-intelligence control system to control a spacecraft without human supervision.
- Remote Agent successfully demonstrated the ability to plan onboard activities and correctly diagnose and respond to faults in spacecraft components through its built-in REPL environment

NASA Deep Space One: Remote Agent

- Autonomous diagnosis & repair “Remote Agent”
- Compiled systems schematic to 7,000 var SAT problem



Deep Space One

- a failed electronics unit
  - Remote Agent fixed by reactivating the unit.
- a failed sensor providing false information
  - Remote Agent recognized as unreliable and therefore correctly ignored.
- an altitude control thruster (a small engine for controlling the spacecraft's orientation) stuck in the "off" position
  - Remote Agent detected and compensated for by switching to a mode that did not rely on that thruster.

Significant progress in Satisfiability Methods

Software and hardware verification – complete methods are critical - e.g. for verifying the correctness of chip design, using SAT encodings

Applications: Hardware and Software Verification Planning, Protocol Design, etc.

Going from 50 variable in, 200 constraints to 1,000,000+ variables and 5,000,000+ constraints in the last 20 years

Progress in Last 25 years

- *Significant progress since the 1990's.* How much?
- Problem size: **We went from 100 variables, 200 constraints (early 90's) to 1,000,000+ variables and 5,000,000+ constraints in 20 years**

- **Search space: from 10^30 to 10^300,000.**
  [Aside: "one can encode quite a bit in 1M variables."]

- **Is this just Moore's Law? It helped, but not much…**
  – 2x faster computers does *not* mean can solve 2x larger instances
  – search difficulty does *not* scale linearly with problem size!
  In fact, for O(2^n), 2x faster, how many more vars?
  handles 1 more variable!!
  Mainly algorithmic progress. Memory growth also key.

- **Tools: 50+ competitive SAT solvers available (e.g. Minisat solver)**
- **See http://www.satcompetition.org/**

Model Checking

Turing Award

2008 Turing Award Winners Announced

Posted by ScuttleMonkey on Monday February 04, @05:30PM
from the **nobel-of-computing-awards** dept.

The Association for Computing Machinery has announced the 2008 Turing Award Winners. Edmund M. Clarke, Allen Emerson, and Joseph Sifakis received the award for their work on an automated method for finding design errors in computer hardware and software.

> "Model Checking is a type of "formal verification" that analyzes the logic underlying a design, much as a mathematician uses a proof to determine that a theorem is correct. Far from hit or miss, Model Checking considers every possible state of a hardware or software design and determines if it is consistent with the designer's specifications. Clarke and Emerson originated the idea of Model Checking at Harvard in 1981. They developed a theoretical technique for determining whether an abstract model of a hardware or software design satisfies a formal specification, given as a formula in Temporal Logic, a notation for describing possible sequences of events. Moreover, when the system fails the specification, it could identify a counterexample to show the source of the problem. Numerous model checking systems have been implemented, such as Spin at Bell Labs."

Source: Slashdot

A “real world” example

From “SATLIB”:

http://www.satlib.org/benchm.html

SAT-encoded bounded model checking instances (contributed by Ofer Shtrichman)

In Bounded Model Checking (BMC) [BCCZ99], a rather newly introduced problem in formal methods, the task is to check whether a given model M (typically a hardware design) satisfies a temporal property P in all paths with length less or equal to some bound k. The BMC problem can be efficiently reduced to a propositional satisfiability problem, and in fact if the property is in the form of an invariant (Invariants are the most common type of properties, and many other temporal properties can be reduced to their form. It has the form of 'it is always true that ... '.), it has a structure which is similar to many AI planning problems.

Bounded Model Checking instance:

The instance bmc-ibm-6.cnf, IBM LSU 1997:

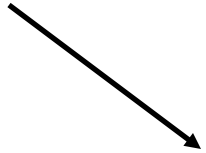
```
p cnf 51639 368352
-1 7 0
-1 6 0
-1 5 0
-1 -4 0
-1 3 0
-1 2 0
-1 -8 0
-9 15 0
-9 14 0
-9 13 0
-9 -12 0
-9 11 0
-9 10 0
-9 -16 0
-17 23 0
-17 22 0
```

i.e. ((not x_1) or x_7) and ((not x_1) or x_6) and … *etc.*

10 pages later:

```
185 −9 0
185 −1 0
177 169 161 153 145 137 129 121 113 105 97
 89 81 73 65 57 49 41
 33 25 17 9 1 −185 0
186 −187 0
186 −188 0
```

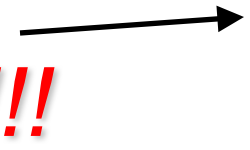
…



(x_{177} or x_{169} or x_{161} or x_{153} …
or x_{17} or x_9 or x_1 or (not x_{185}))

clauses / constraints are getting more interesting…

4000 pages later:



!!!

a 59-cnf clause…

```
10236 −10050 0
10236 −10051 0
10236 −10235 0
10008 10009 10010 10011 10012 10013 10014
 10015 10016 10017 10018 10019 10020 10021
 10022 10023 10024 10025 10026 10027 10028
 10029 10030 10031 10032 10033 10034 10035
 10036 10037 10086 10087 10088 10089 10090
 10098 10099 10100 10101 10102 10103 10104
 10105 10106 10107 10108 −55 −54 53 −52 −51 50
 10047 10048 10049 10050 10051 10235 −10236 0
10237 −10008 0
10237 −10009 0
10237 −10010 0
```

…

Finally, 15,000 pages later:

```
−7 260 0
7 −260 0
1072 1070 0
−15 −14 −13 −12 −11 −10 0
−15 −14 −13 −12 −11 10 0
−15 −14 −13 −12 11 −10 0
−15 −14 −13 −12 11 10 0
−7 −6 −5 −4 −3 −2 0
−7 −6 −5 −4 −3 2 0
−7 −6 −5 −4 3 −2 0
−7 −6 −5 −4 3 2 0
185 0
```

Note that: $2^{50000} \approx 3.160699437 \cdot 10^{15051}$ *… !!!*

MiniSAT solver solves
this instance in less than one minute.