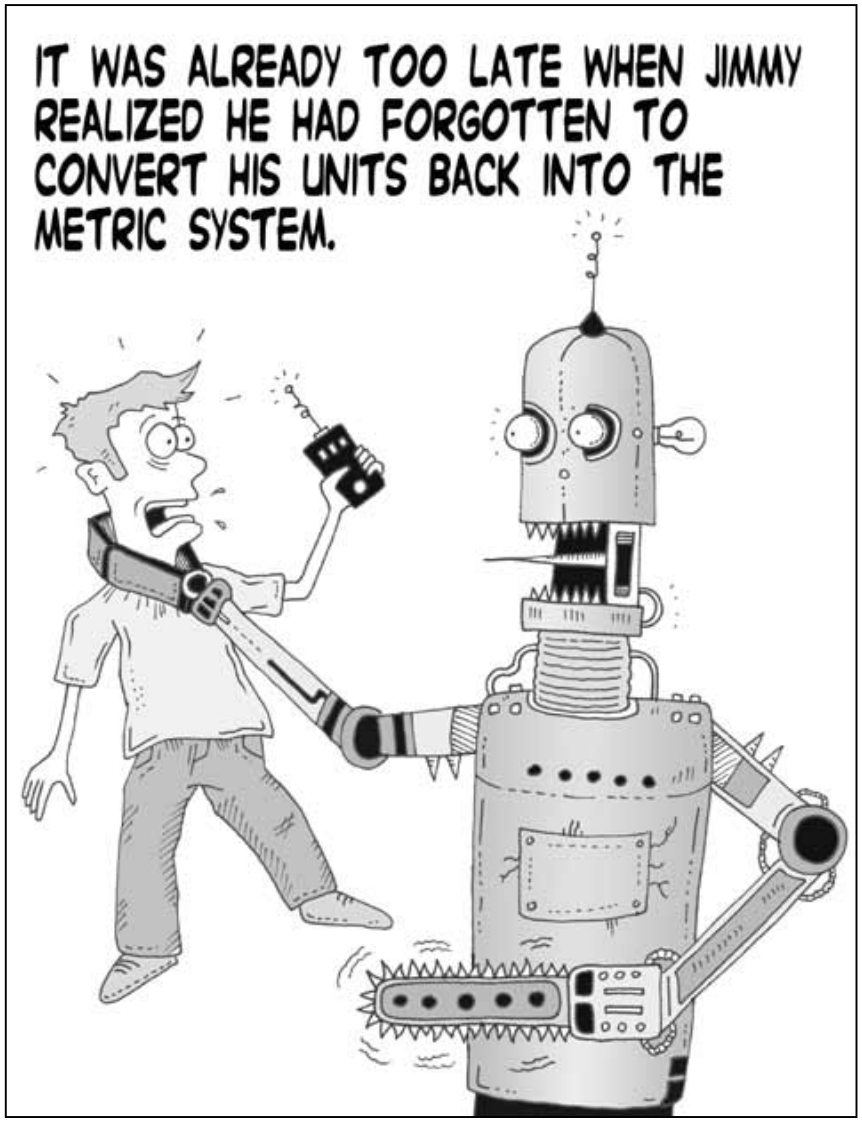
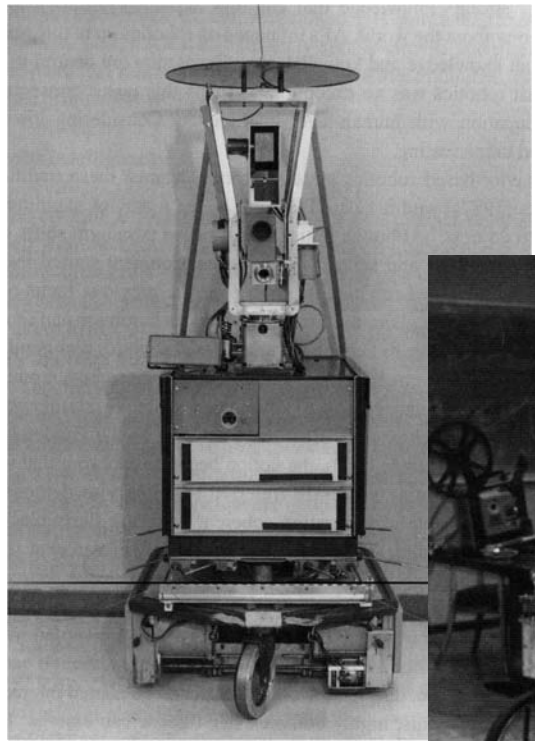
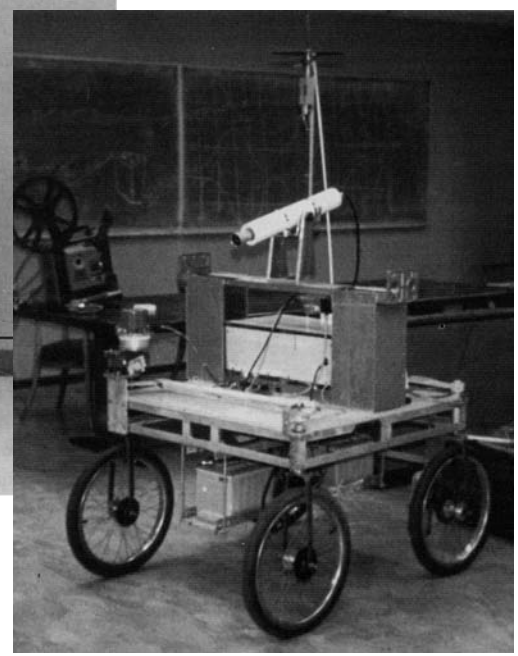
Hierarchical Paradigm and STRIPS

January 25, 2007
Class Meeting 4





Shakey



Stanford Cart

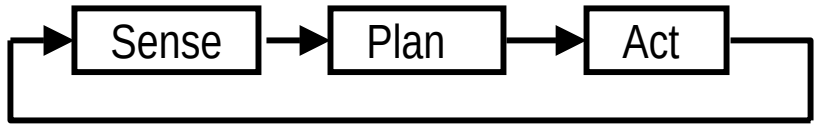
Objectives

- To understand organizational differences between 3+ robot control paradigms
- To understand distinction between problem solver and planner
- To understand methods used by problem solvers
- To understand STRIPS approach to problem solving
- To understand example hierarchical architectures NHC and RCS

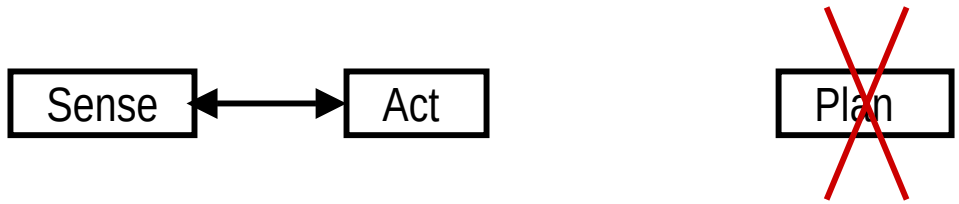
Recall: Three+ Primary Control Paradigms

(compare to Figure I.3 in Murphy, pg. 7)

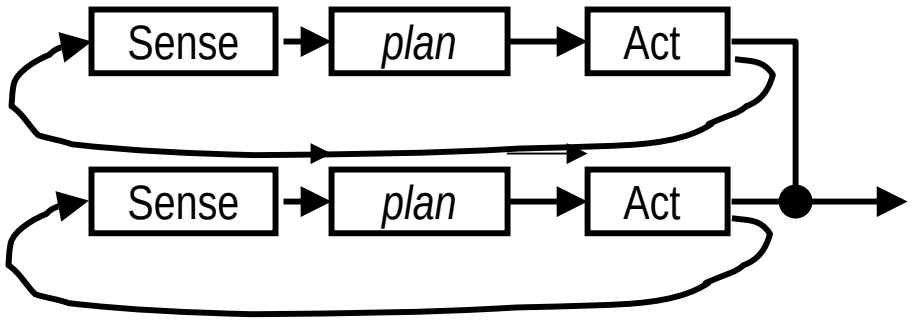
1. Hierarchical:



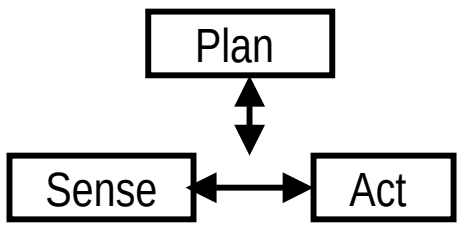
2. Reactive:



2+. Behavior-Based:

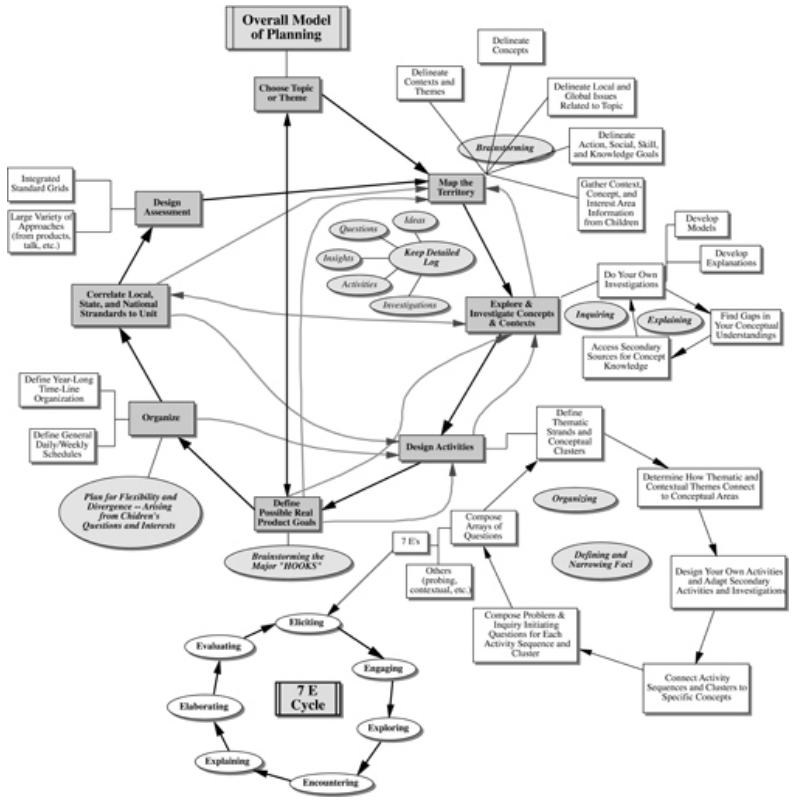


3. Hybrid deliberative/reactive:



Planning vs. Problem Solving

- Planning agent is very similar to problem-solving agent
  - Constructs plans to achieve goals, then executes them
- Planning agent is different from problem-solving agent in:
  - Representation of goals, states, actions
  - Use of explicit, logical representations enables more sensible deliberations of potential solutions
  - Way it searches for solutions



(just an example of complicated planning/problem solving)

Problem Solver Characteristics

- Search-based problem solver:
  - Representation of actions: programs that generate successor state descriptions
  - Representation of states: complete state descriptions; typically, data structure holding permutations of all possible states
  - Representation of goals: goal test and heuristic function to decide desirability
  - Representation of plans: solution is sequence of actions; considers only unbroken sequences of actions

Famous Problem Solver Task: “Missionaries and Cannibals”

- “Missionaries and cannibals” problem:
  - Famous in AI
  - Was subject of first paper (Amarel, 1968) that approached problem formulation from analytical viewpoint
  - Problem statement:
    - 3 missionaries and 3 cannibals on one side of river, with boat that can hold 1-2 people
    - Find: way to get everyone to other side of river, without ever leaving group of missionaries in one place outnumbered by cannibals in that place

Formalizing Missionaries and Cannibals Problem

- Ignore all irrelevant parts of the problem (e.g., weather conditions, crocodiles, etc.)
- Define states, operators, goal test, path cost:
  - States: ordered sequence of 3 numbers:
    - (# missionaries, # cannibals, #boats on initial riverbank)
    - E.g.: Start state = (3, 3, 1)
  - Operators:
    - Take 1 missionary, 1 cannibal, 2 missionaries, 2 cannibals, or one of each across in boat.
    - Take care to avoid illegal states
  - Goal test:
    - We've reached state (0, 0, 0)
  - Path cost:
    - # of crossings

Solving Missionaries and Cannibals Problem

(3, 3, 1)

X (2, 3, 0)

(3, 2, 0)

X (1, 3, 0)

(3, 1, 0)

(2, 2, 0)

(3, 2, 1)

X (2, 3, 1)

(2, 2, 0)

X (1, 2, 0)

(3, 0, 0)

(2, 1, 0) X

(3, 1, 1)

(1, 1, 0)

(2, 2, 1)

(2, 2, 1)

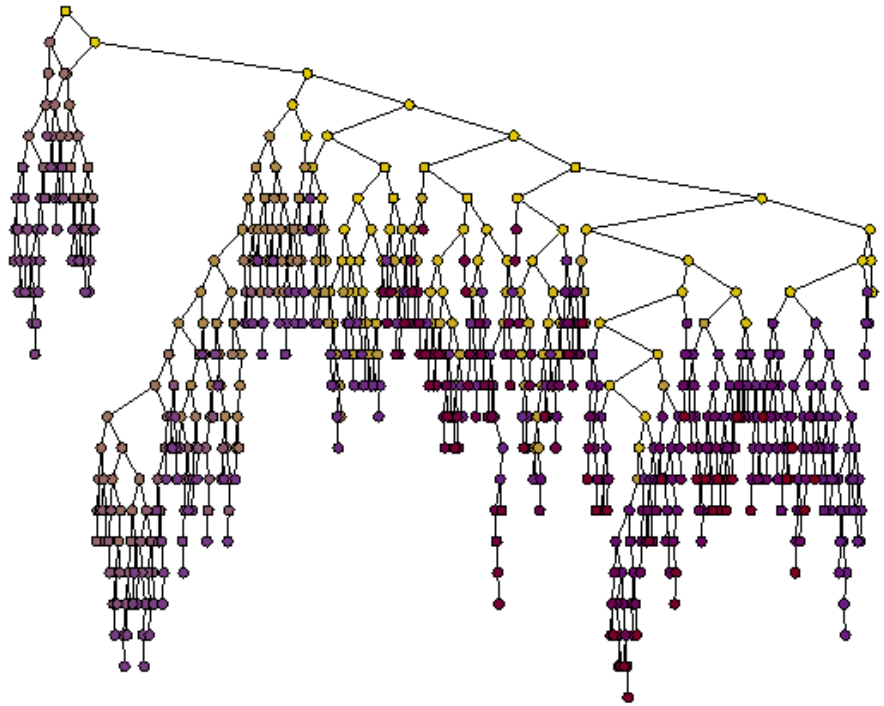
etc. → (0, 0, 0)

Search Strategies for Problem Solvers

- Key criteria:
  - Completeness: is strategy guaranteed to find a solution when one exists?
  - Time complexity: how long does it take to find solution?
  - Space complexity: how much memory is needed to find solution?
  - Optimality: does strategy find highest-quality solution?

Alternative Search Strategies for Problem Solvers

- Variety of search approaches:
  - Uninformed search (no information about path cost from current state to goal):
    - Breadth-first
    - Uniform cost search
    - Depth-first
    - Depth-limited search
    - Iterative deepening
    - Bidirectional
    - Etc.
  - Informed search
    - Greedy
    - A*
    - Hill-climbing/gradient descent
    - Simulated annealing
    - Etc.



(a messy search tree)

Important Points Regarding Problem Solvers

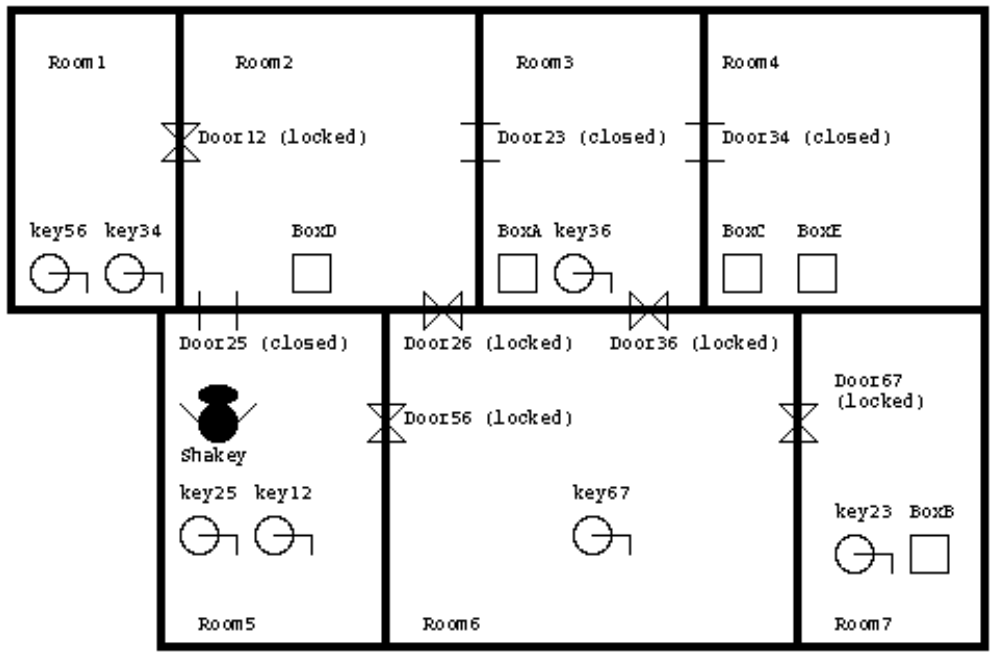
- Search-based problem solver:
  - Representation of states: *complete* state descriptions; typically, data structure holding permutations of all possible states
  - Representation of goals: goal test and heuristic function to decide desirability; cannot "look inside" to select actions that might be useful for achieving goal
  - Representation of plans: solution is sequence of actions; considers only unbroken sequences of actions from start to goal

From Problem Solvers to Planners

- Key ideas:
  - "Open up" representation of states, goals, and actions
    - Use descriptions in a formal language – usually first-order logic
    - States/goals represented by sets of sentences
    - Actions represented by logical descriptions of preconditions and effects
    - Enables planner to make direct connections between states and actions
  - Planner can add actions to plan whenever needed, rather than in strictly incremental fashion
    - No necessary connection between order of planning and order of execution
    - Note that planner states are equivalent to entire classes of problem-solver states
  - Most parts of the world are independent of most other parts of the world
    - Conjunctions can be separated and handled independently
    - Divide-and-conquer algorithms: efficient because it is easier to solve several small sub-problems rather than one big problem

Planning-Based Approach to Robot Control

- Job of planner: generate a goal to achieve, and then construct a plan to achieve it from the current state.
- Must define representations:
  - Representation of actions: programs that generate successor state descriptions, defining preconditions and effects
  - Representation of states: data structure describing current situation
  - Representation of goals: what is to be achieved
  - Representation of plans: solution is a sequence of actions



First-order logic and theorem proving enable planning of strategies from start state to goal

Recall: First Order Predicate Calculus in AI

- First order predicate calculus: formal language useful for making inferences and deductions
- Elementary components:
  - Predicate symbols (e.g., WRITES(), LIVES(), OWNS(), MARRIED())
  - Variable symbols (e.g., *x, y)*
  - Function symbols (e.g., *father(x)* returns the father of *x*)
  - Constant symbols (e.g., HOUSE-1, NERO, GEORGE-BUSH)
  - Connectives
    - and, or, negation, implies $\wedge, \vee, \neg, \Rightarrow$
  - Quantification
    - Universal $\forall x$
    - Existential $\exists x$
- NOTE: *First order* means quantification over predicates or functions not allowed

Situation Calculus

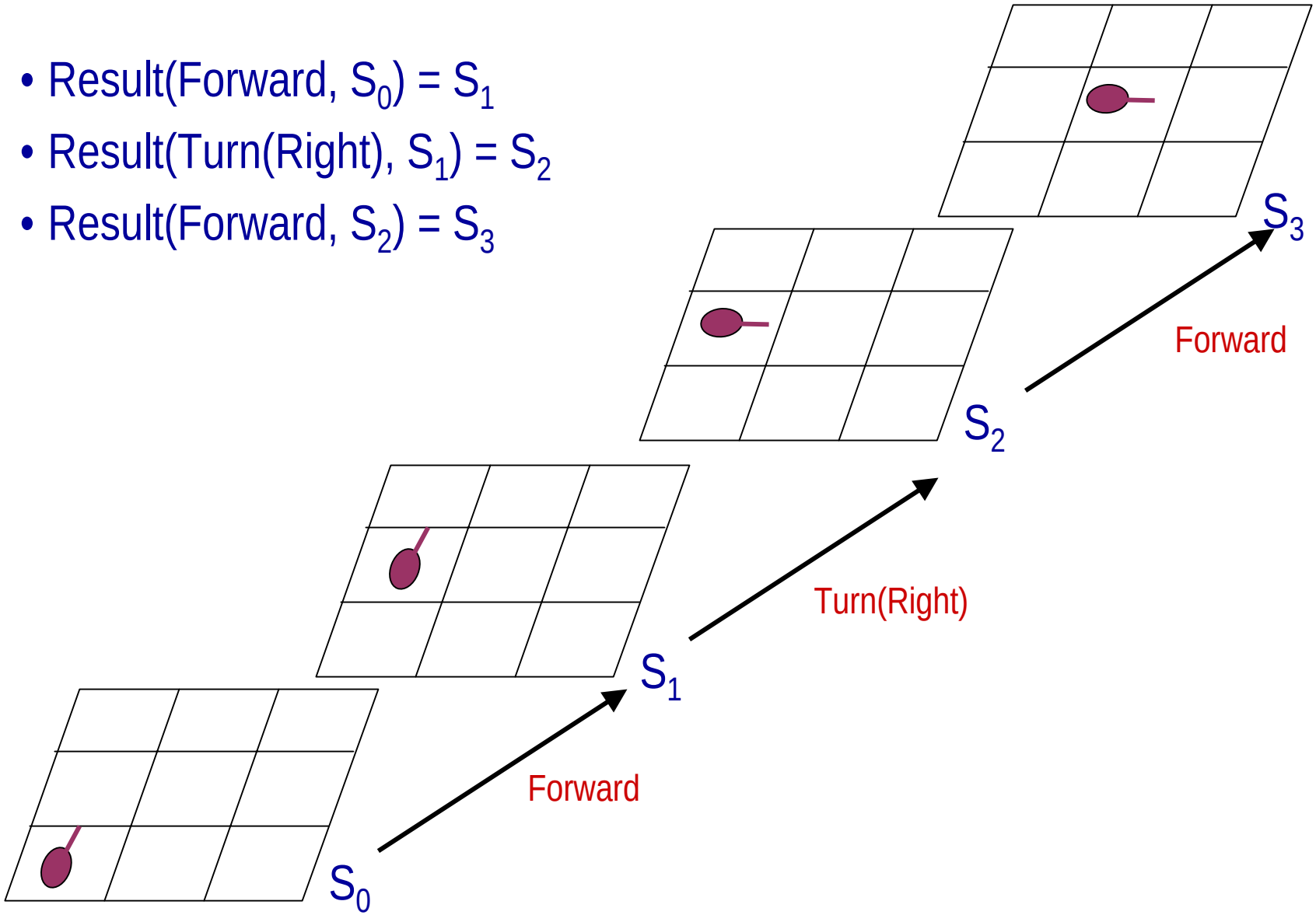
- Situation calculus:
  - Refers to a particular way of describing change in first-order logic
  - Conceives of world as consisting of a sequence of *situations*, each of which is a snapshot of the state of the world

- All relations/properties of world that can change over time:
  - Specify extra situation argument to predicate
  - Instead of: At(agent, location)
  - Indicate: At(agent, location, S_i), where S_i is a particular situation, or point in time

- Represent how world changes from one situation to next:
  - Result(Forward, S_0) = S_1
  - Result(Turn(Right), S_1) = S_2
  - Results(Forward, S_2) = S_3

Example of World Represented by Situation Calculus

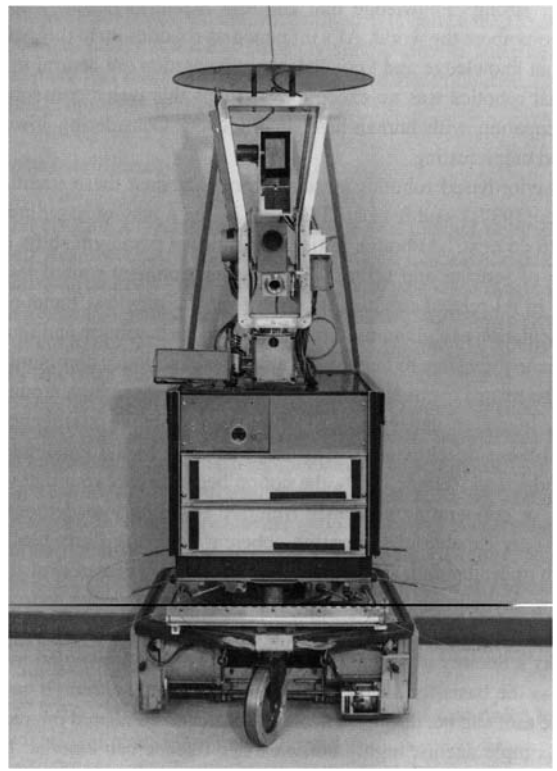
- Result(Forward, S_0) = S_1
- Result(Turn(Right), S_1) = S_2
- Result(Forward, S_2) = S_3



STRIPS-Based Approach to Robot Control

- Use first-order logic and theorem proving to plan strategies from start state to goal

- STRIPS language:
  - "Classical" approach that most planners use
  - Lends itself to efficient planning algorithms
  - Retains expressiveness of situation calculus



Shakey (SRI), 1960's

STRIPS Representation – States and Goals

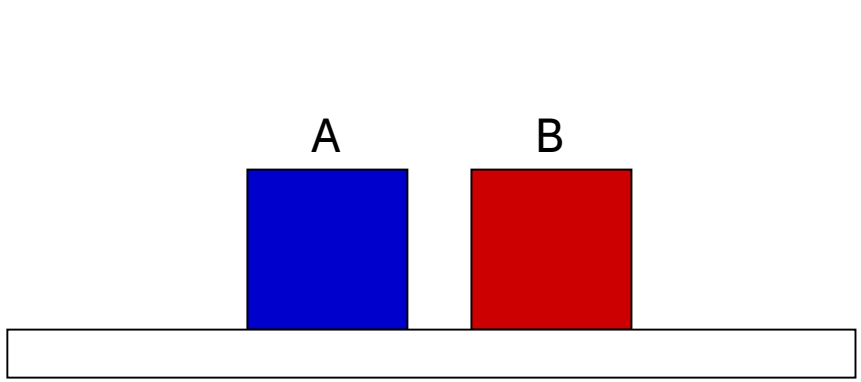
- States: Conjunctions of function-free ground literals (i.e., predicates applied to constant symbols, possibly negated)
  - Example: At(Home) Have(Milk) Have(Bananas)
  - Common assumption: If state description does not mention a given positive literal, then the literal is assumed to be false
- Goals: Conjunctions of literals, which can include variables
  - Example: At(x) Sells(x,Milk)
  - Assumption: variables are existentially quantified

STRIPS Representation -- Actions

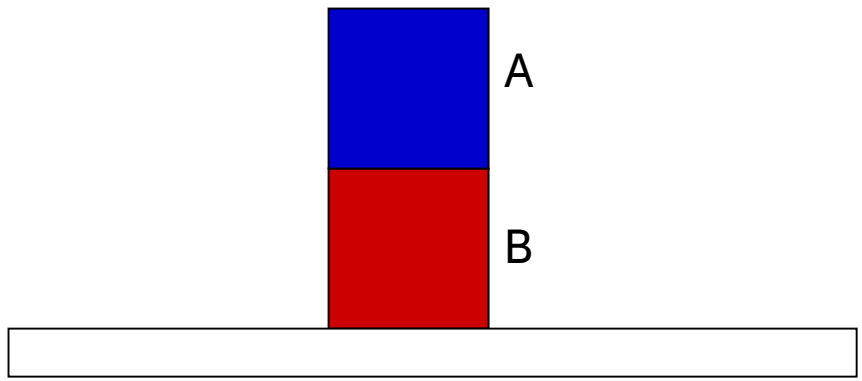
- STRIPS operators consist of:
  - Action description: name for what an agent does
  - Precondition: conjunction of positive literals (atoms) saying what must be true before operator can be applied
  - Effect: conjunction of literals (positive or negative) that describes how the situation changes when operator is applied
    - Organize effect as:
      - ADD LIST
      - DELETE LIST

Recall: Simple Example of STRIPS Blocks-World Problem

- Goal State: ON(A,B)
- Start state: ON(A, Table); ON(B, Table); EMPTYTOP(A); EMPTYTOP(B)
- Operator:
  - MOVE(x,y):
    - Preconditions: ON(x,Table); EMPTYTOP(y)
    - Add-List: ON(x,y)
    - Delete-List: EMPTYTOP(y); ON(x,Table)



Start State



Goal State

Shakey's STRIPS World

- Types of actions Shakey can make (at least in simulation):
  - Move from place to place:

    Go(y):

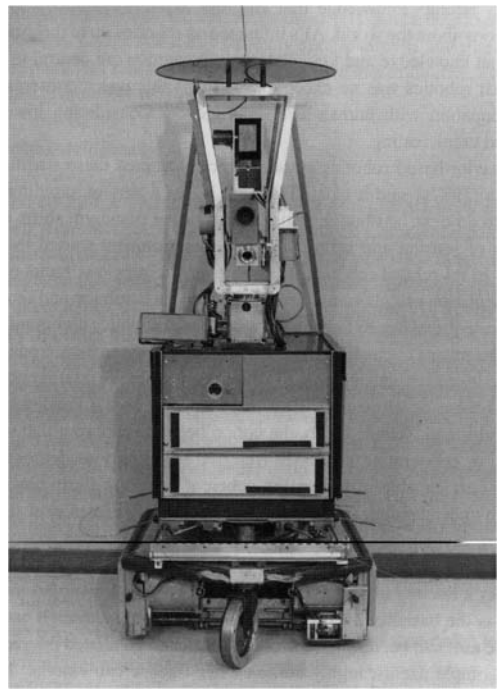
    PRECOND: At(Shakey,x)
    In(x,r) $\wedge$ In (y,r)
    On(Shakey,Floor)

    EFFECT: At(y)
  - Push movable objects:

    Push(b, x, y):

    PRECOND: Pushable(b)
    At(b,x)
    At(Shakey,x)
    In(x,r) $\wedge$ In (y,r)
    On(Shakey,Floor)

    EFFECT: At(b,y)



Shakey's STRIPS World (con't.)

- Types of actions Shakey can make (at least in simulation):
  - Climb onto rigid objects:

    Climb(b):

    PRECOND: Climbable(b)

    At(Shakey,x) $\wedge$ At(b,x)

    On(Shakey,Floor)

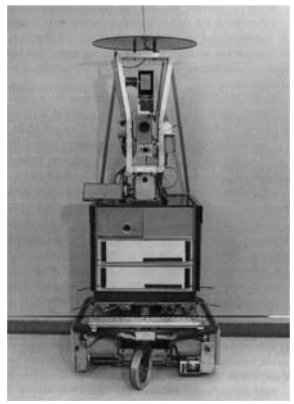
    EFFECT: On(Shakey,b)

  - Climb down from rigid objects:

    (etc.)

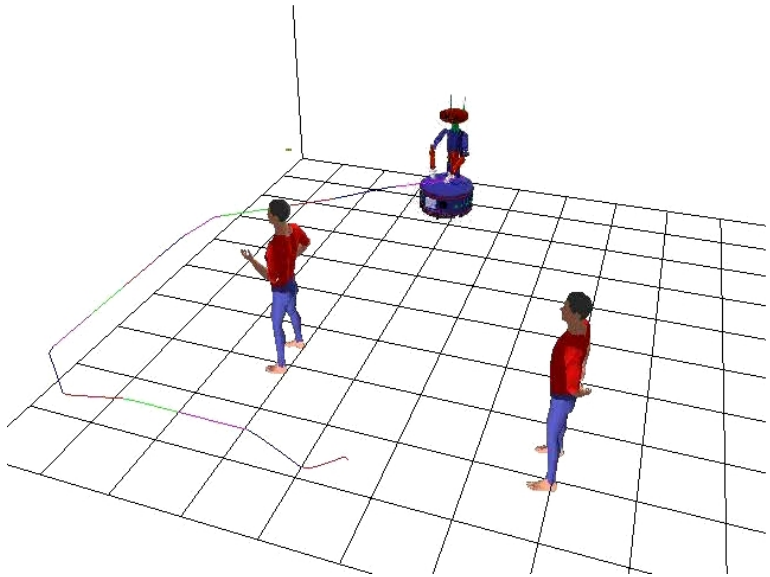
  - Turn light switches on and off:

    (etc.)



STRIPS Representation -- Plans

- A *Plan* is a data structure consisting of:
  - A set of plan steps.
    - Each step is one of operators for the problem.
  - A set of step ordering constraints. $S_i \prec S_j$
    - Ordering constraints specify that an action has to occur sometime before another action
  - A set of variable binding constraints.
    - Variable constraints are of form v=x, where v is variable at some step, and x is either a constant or a variable
  - A set of causal links.
    - Record the purpose of the steps in the plan.
    - E.g., purpose of S_i is to achieve the precondition c of S_j.



How to Develop a Plan in STRIPS?

- Use “means-ends analysis”
  - If robot is not at goal, then measure the distance (or difference) between the robot’s current state and its goal state
  - Find an operator that the robot can take that will reduce this distance (difference), and select it if can bind the variables in preconditions to make preconditions true
  - Make the first false precondition of this operator the new “subgoal”, remembering old goal by pushing on stack
  - Recursively reduce difference by repeating above.
  - When all preconditions for operator match, add the operator to the plan stack and update world model. Continue until we find an operator that can be executed in robot’s current state
  - When done, pop the actions off the stack to create the plan from start to goal.

Generating Plans in STRIPS

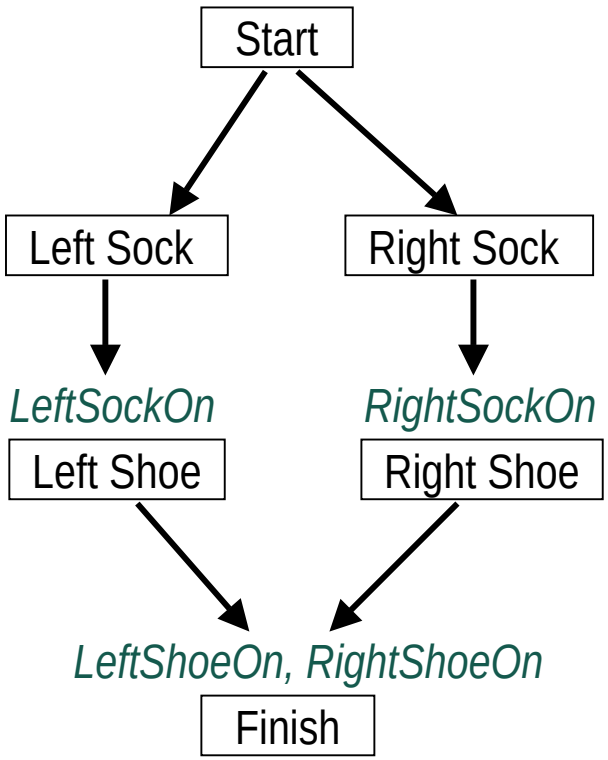
- Use principle of least commitment:
  - Make choices only regarding things you care about; leave others for later
  - Leave ordering of steps unspecified if it doesn't matter for now
  - Plan in which some steps are ordered and others aren't: partial order plan (as compared to a total order plan):

- "Instantiate": bind a variable to a constant
  - Example:
    - At(Shakey,x) ➔ At(Shakey, Home)
    - Variable x is bound to constant "Home"

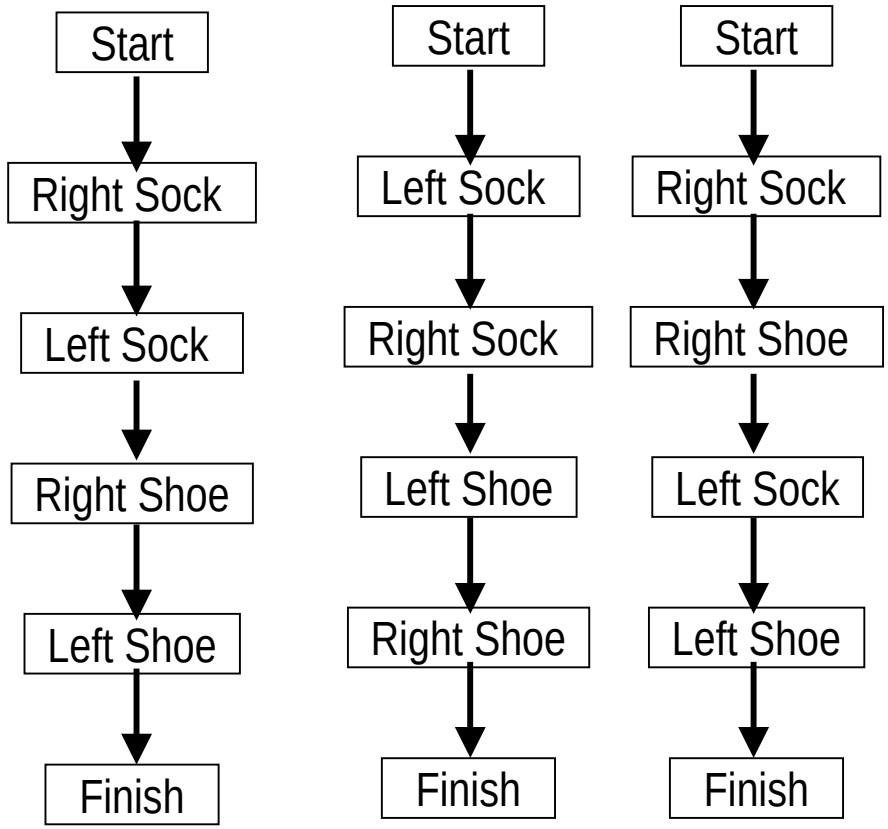
- Fully instantiated plans:
  - Plans in which every variable is bound to a constant

Partial Order vs. Total Order Plans

Partial Order Plan:



Total Order Plans:



Etc.

Solutions in STRIPS

- Solution: plan that an agent can execute, and that guarantees achievement of goal

- Easy way to make guarantee:
  - Require only fully instantiated, totally ordered plans

- However, not satisfactory, because:
  - Easier for planners to return partially ordered plan than to arbitrarily select from alternative total orderings
  - Some agents can perform actions in parallel
  - Want to maintain flexibility of plan execution, in case other constraints arise later

Solutions in STRIPS (con't.)

- Therefore, solution is:
  - A Complete, Consistent plan
- Complete plan:
  - One in which every precondition of every step is achieved by some other step
  - One in which preconditions are not "un-done" by another step prior to its need in a given step
- Consistent plan:
  - One in which there are no contradictions in the ordering or binding constraints

Example Algorithm for Partial-Order Planner (POP)

POP: A sound, complete partial order planner using STRIPS representation

```
function POP(initial, goal, operators) returns plan
  plan ← MAKE-MINIMAL-PLAN(initial, goal)
  loop do
    if SOLUTION?(plan) then return plan
    S_need, c ← SELECT-SUBGOAL(plan)
    CHOOSE-OPERATOR(plan, operators, S_need, c)
    RESOLVE-THREATS(plan)
  end
```

where: * c is a precondition of a step S_{need}

* RESOLVE-THREATS: orders steps as needed to ensure intermediate steps don't undo preconditions needed by other steps

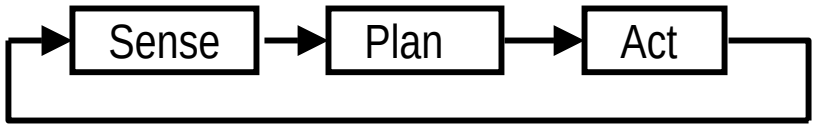
Summary of the Planning Problem

- Planning agents use look-ahead to find actions to contribute to goal achievement
- Planning agents differ from problem solvers in their use of more flexible representation of states, actions, goals, and plans
- The STRIPS language describes actions in terms of preconditions and effects, capturing much of the expressive power of situational calculus
- It is infeasible to search through space of situations; therefore, search through space of plans
- Principle of least commitment is preferred
- POP is a sound and complete algorithm for planning using STRIPS representation

Hierarchical Architectures

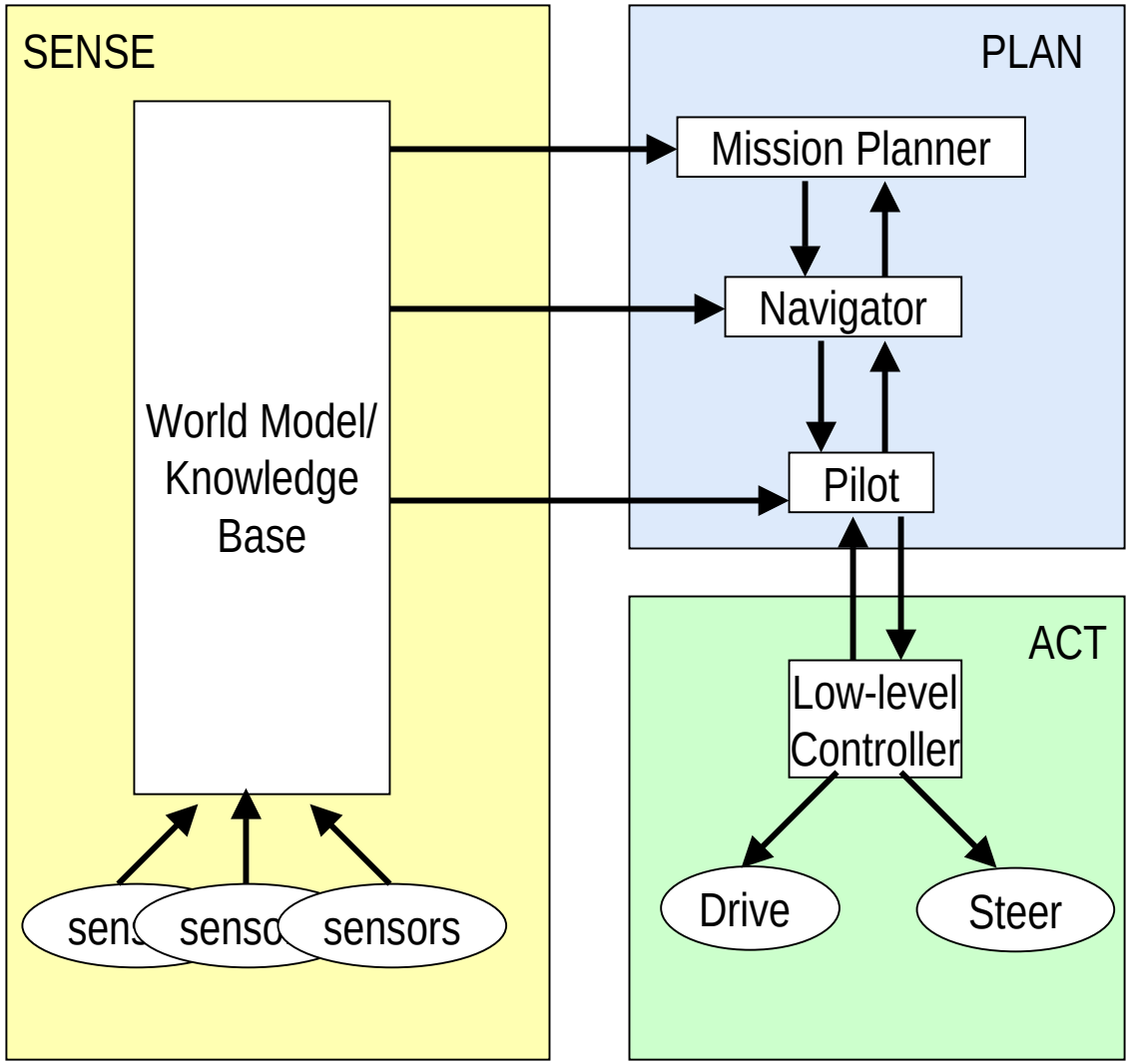
- "Architecture": a method of implementing a control paradigm, of embodying certain principles in a concrete way

- Hierarchical paradigm:



- Two best-known hierarchical architectures:
  - Nested Hierarchical Controller (NHC) – developed by Meystel
  - NIST Realtime Control System (RCS), adapted to a teleoperation version called NASREM – developed by Albus

Nested Hierarchical Controller



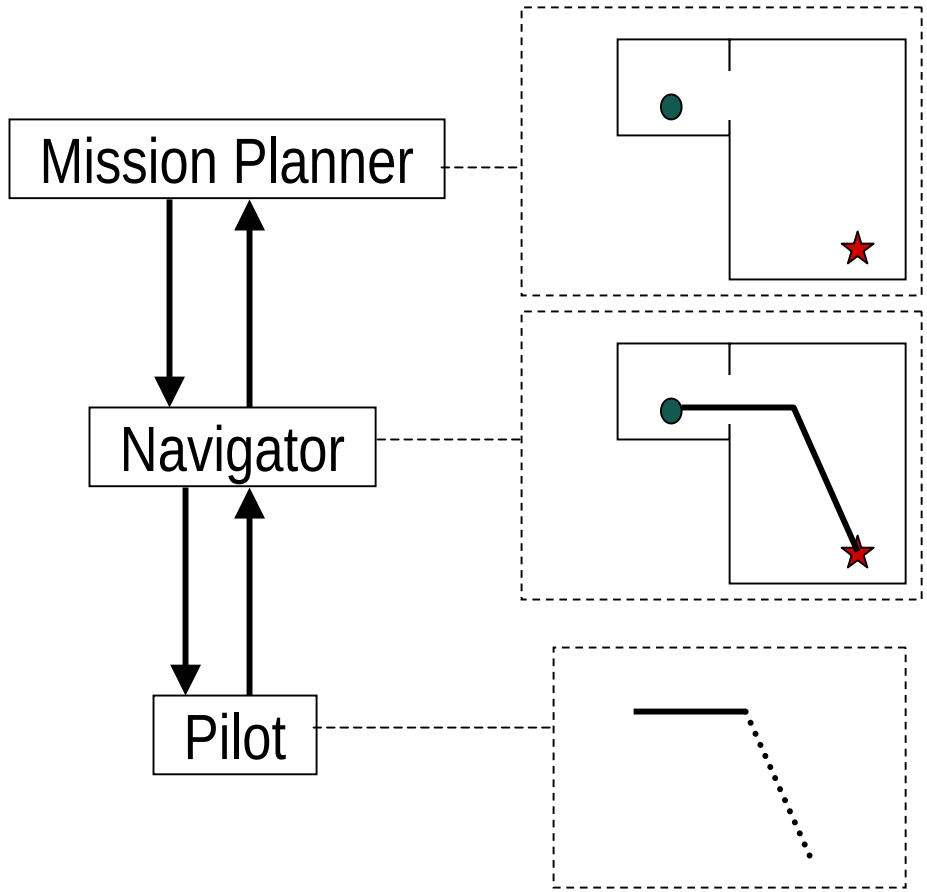
Major contribution of NHC: Decomposition of planning into three subsystems

Planning is Hierarchical

Uses map to locate self and goal

Generates path from current position to goal

Generates actions robot must execute to follow path segment

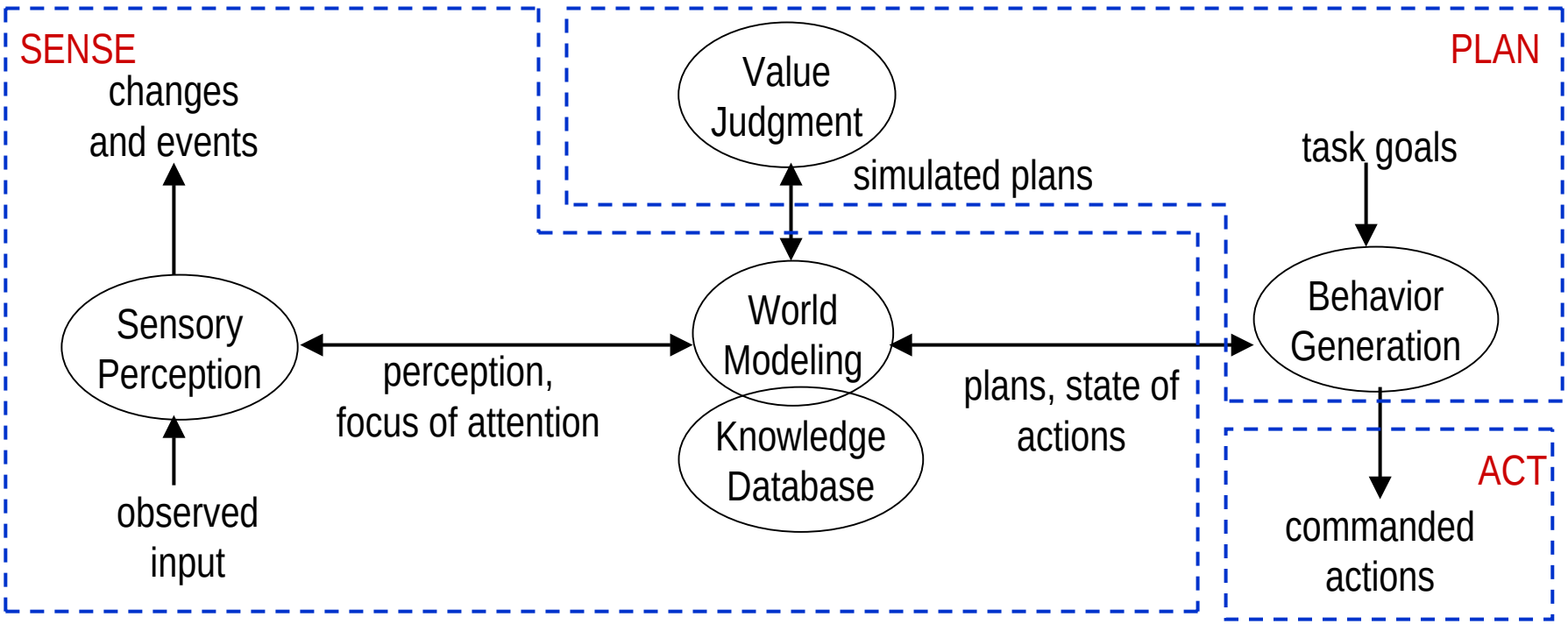


Advantage/Disadvantage of NHC

- Advantage:
  - Interleaves planning and acting (unlike STRIPS)
    - Plan is changed if world is different from expected
- Disadvantage:
  - Planning decomposition is only appropriate for navigation tasks

A Second Hierarchical Architecture: NIST RCS & NASREM

- NIST RCS: developed to serve as standard for manufacturers' development of more intelligent robots
- Similar in design to NHC
  - Primary difference: sensory perception includes preprocessing (feature extraction, or focus of attention)



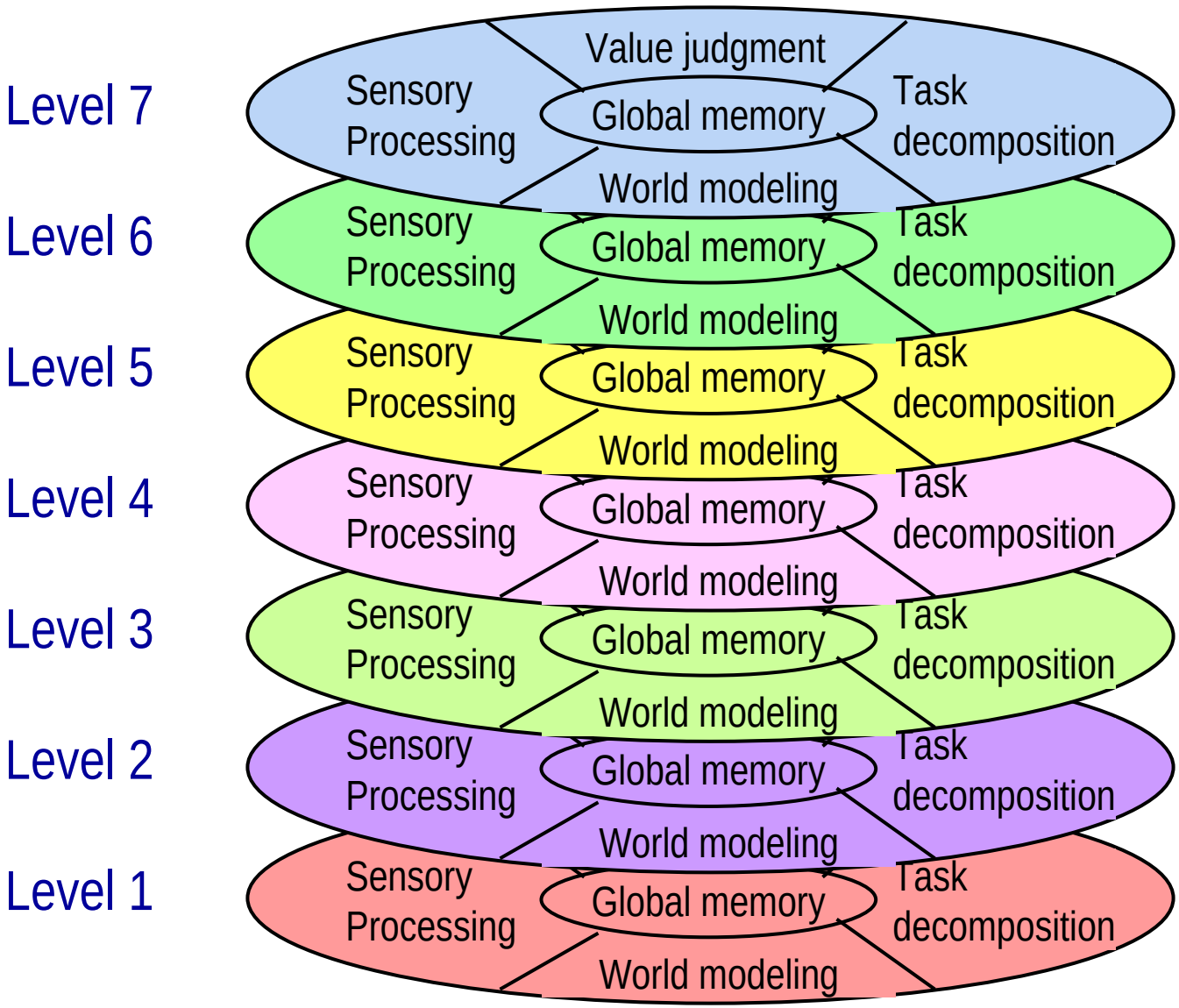
Multiple Layers of NIST RCS & NASREM

- Each layer has:
  - Sensory processing
  - World modeling
  - Task decomposition
  - Value judgment
- All layers joined by global memory through which representational knowledge is shared
- Perception is not tied directly to action

NASREM Endorsed as Standard Model in 1980's

- Six levels capture specific functionalities:
  - Servo
  - Primitive
  - Elemental move
  - Task
  - Service bay
  - Service mission
- Despite government endorsement, only limited acceptance; considered to detailed and restrictive by many AI researchers

Multiple Levels of NIST RCS & NASREM



Example levels:

- Service Mission
- Service Bay
- Task
- Elemental Move
- Primitive
- Servo

NHC and RCS/NASREM: Well-Suited for Semi-Autonomous Control

- Human operator could:
  - Provide world model
  - Decide mission
  - Decompose mission into plan
  - Decompose plan into actions
- Lower-level controller (robot) could:
  - Execute actions
- As robot gets “smarter”, replace more functions and “move up” autonomy hierarchy

Evaluation of Hierarchical Architectures

- Robots (other than Walter's tortoise and Braitenberg's vehicles) built before 1985 typically used hierarchical style of software organization
- Primary advantage of Hierarchical Paradigm:
  - Provides ordering of relationship between sensing, planning, and acting
- Primary disadvantages of Hierarchical Paradigm:
  - Planning
    - Every update cycle, robot had to update global world model, then plan
  - Sensing and acting are always disconnected
  - Appropriate hierarchical decomposition is application-dependent
  - Uncertainty not well-handled

Preview of Next Class

- Begin looking at Reactive and Behavior-Based Paradigms
- Biological Foundations of Reactive and Behavior-Based Systems