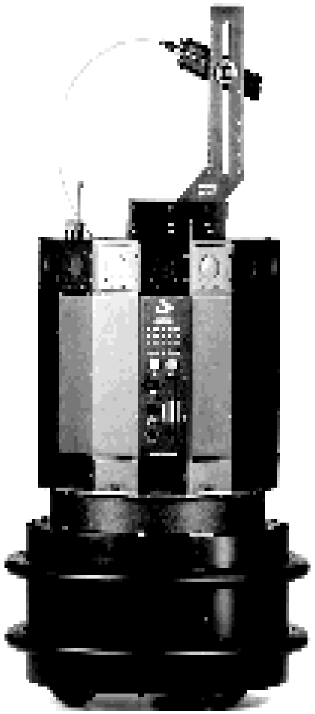
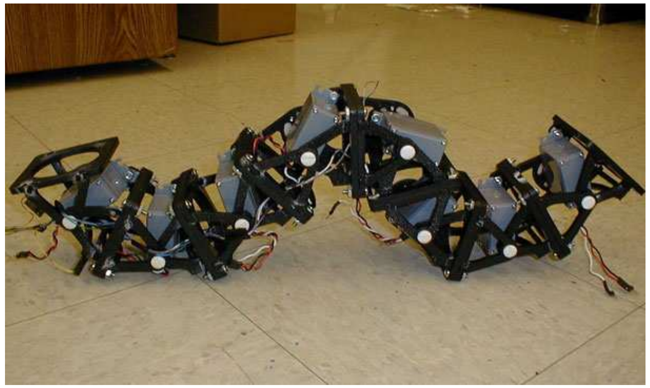
History of Intelligent Mobile Robotics



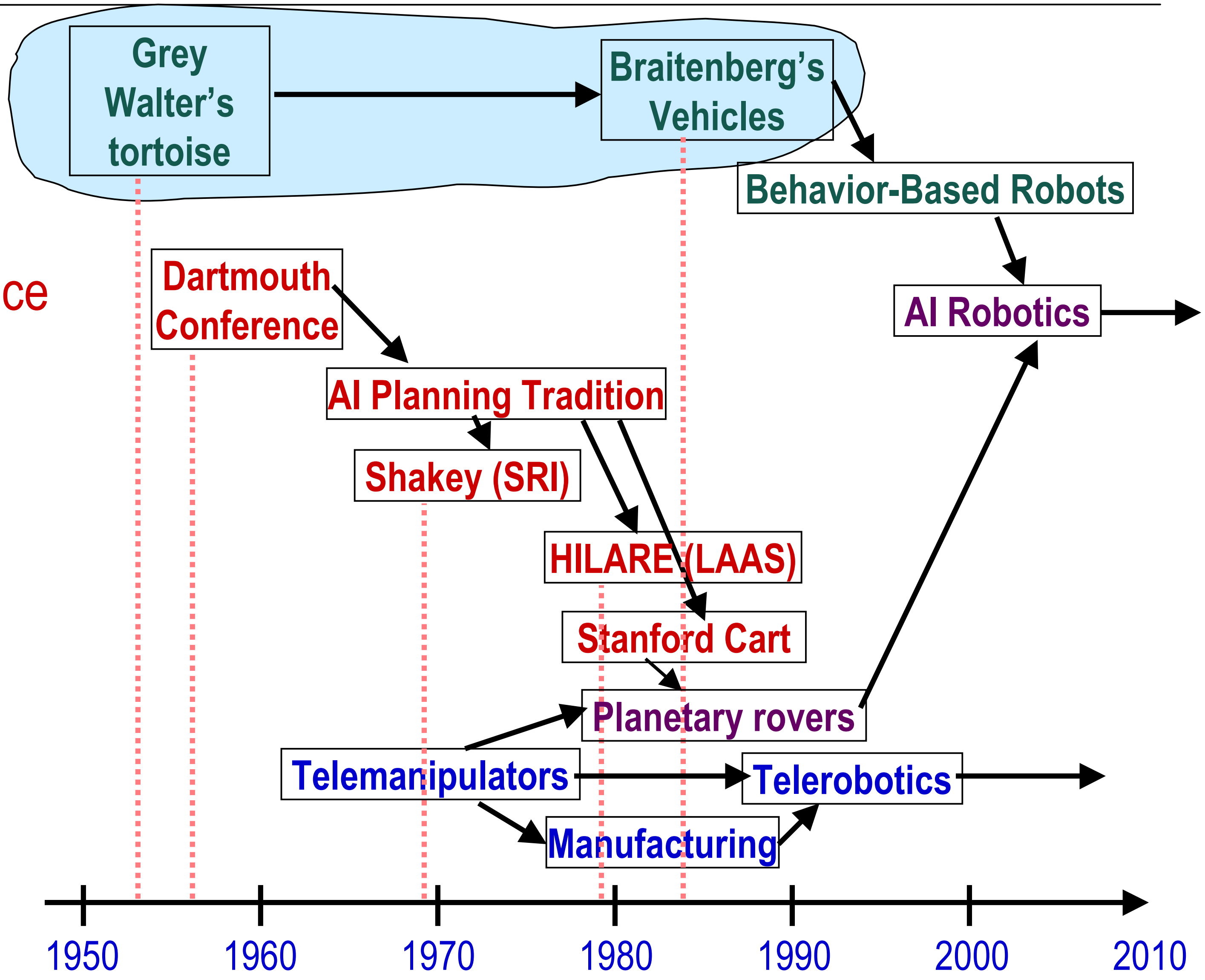


Objectives

- Understand historical precursors to intelligent robotics:
  - Cybernetics
  - Artificial Intelligence
  - Robotics
- Become familiar with key milestones in development of intelligent robotics
- Understand overall approaches to robotic control taken by historical precursors

Historical Precursors to Today's Intelligent Robotics

- Cybernetics
- Artificial Intelligence
- Robotics



Cybernetics

- Cybernetics is combination of:
  - Control theory
  - Information science
  - Biology
- Seeks to explain control principles in both animals and machines
- Uses mathematics of feedback control systems to express natural behavior
- Emphasis is on *situatedness* -- strong two-way coupling between organism and its environment
- Leader of cybernetics field: Norbert Wiener in late 1940s

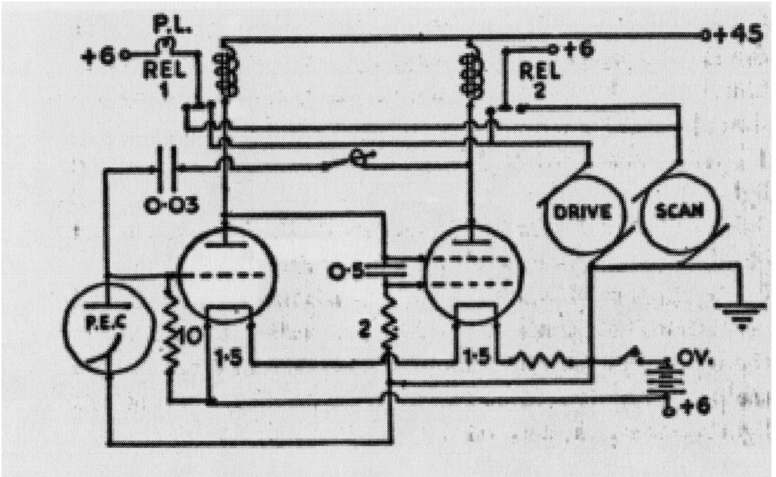
W. Grey Walter

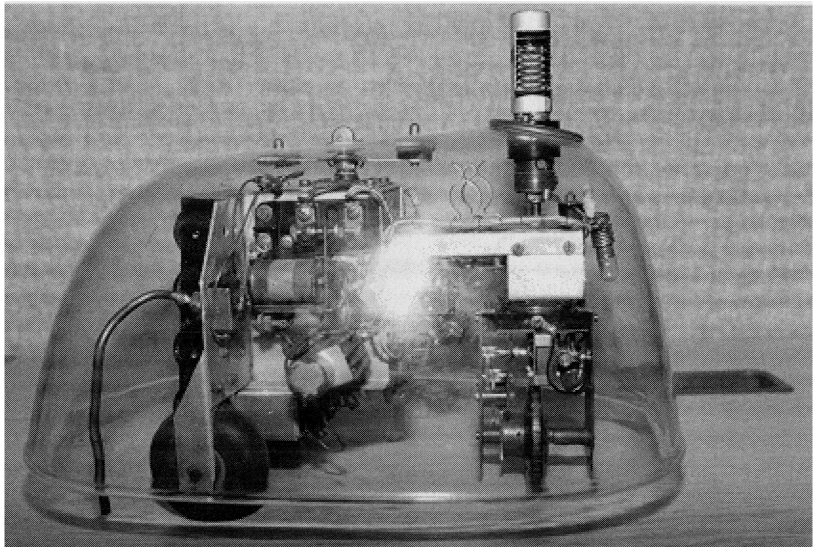
- Born in Kansas City in 1910, but raised in Cambridge, England
- Did work in 1920s with EEG

- Showed that certain patterns indicated person is learning
- Led to work in artificial intelligence and robotics

W. Grey Walter and one of his robots

Grey Walter's *Machina Speculatrix*, or Tortoise (1953)





- Sensors:
  - Photocell
  - Contact
- Actuators:
  - Steering motor on wheel
  - Driving motor on wheel
- Behaviors of tortoise:
  - Seeking light
  - Head toward weak light
  - Back away from bright light
  - Turn and push (for obstacle avoidance)
  - Recharge battery

Principles Learned from Walter's Tortoise

- Parsimony: simple is better
- Exploration or speculation: constant motion motion to avoid traps
- Attraction (positive tropism): move towards positive stimuli
- Aversion (negative tropism): move away from negative stimuli
- Discernment: distinguish between productive and unproductive behavior

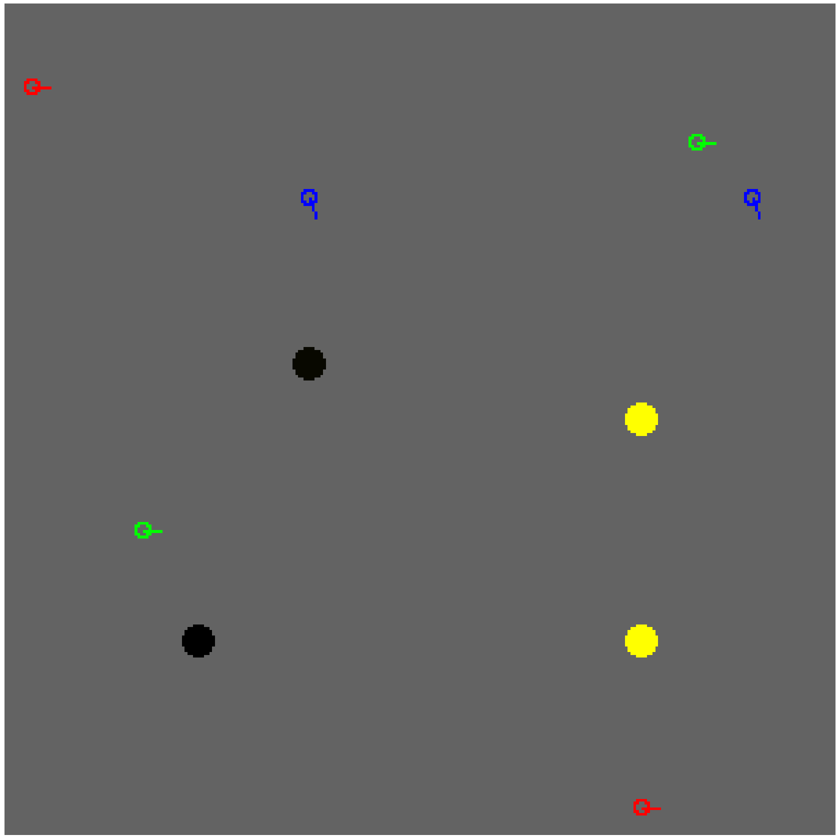
Braitenberg's Vehicles (1984)

- Took perspective of psychologist
- Created wide range of vehicles
- Vehicles used inhibitory and excitatory influences
- Direct coupling of sensors to motors
- Exhibited behavioral characteristics that appeared to be:
  - Cowardice
  - Aggression
  - Love
  - (Etc.)

Valentino Braitenberg
Former Director
Max Plank Institute for Biological Cybernetics, Germany

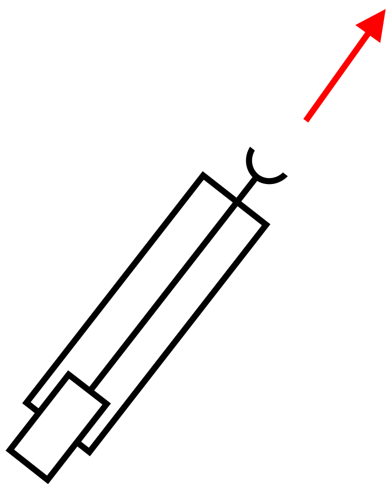
What behaviors do you see?

- (Movie of some of Braitenberg's vehicles)



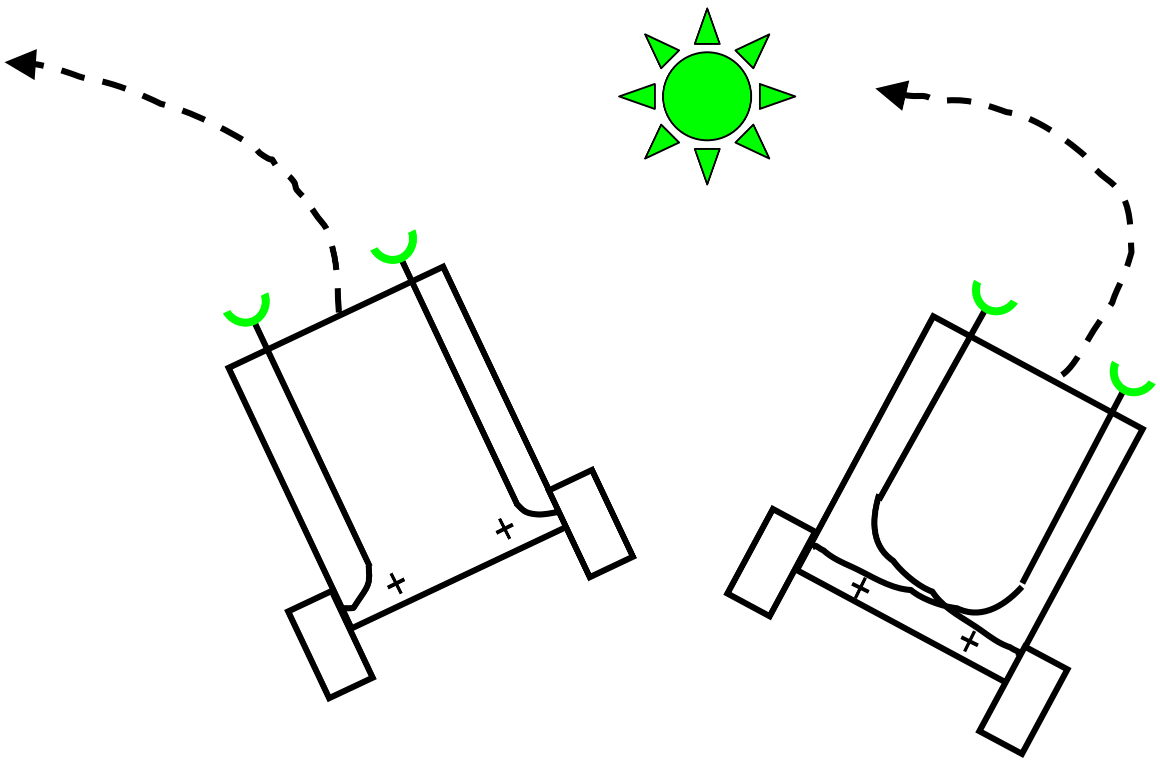
Braitenburg Vehicle 1: "Getting Around"

- Single motor, single sensor
- Motion always forward
- Speed controlled by sensor
- Environmental perturbations produce direction changes



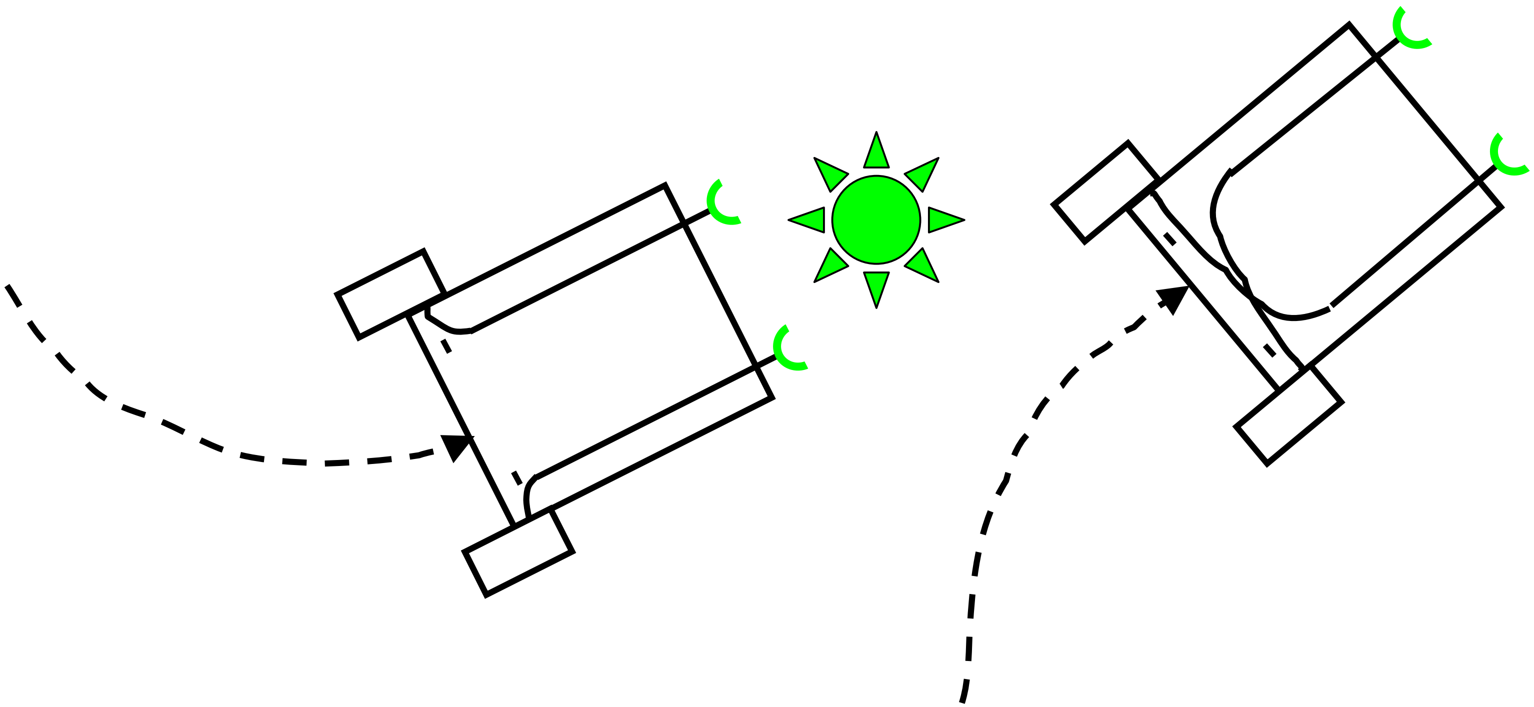
Braitenburg Vehicle 2: "Fear and Aggression"

- Two motors, two sensors
- One configuration: light aversive ("fear")
- Second configuration: light attractive ("aggression")



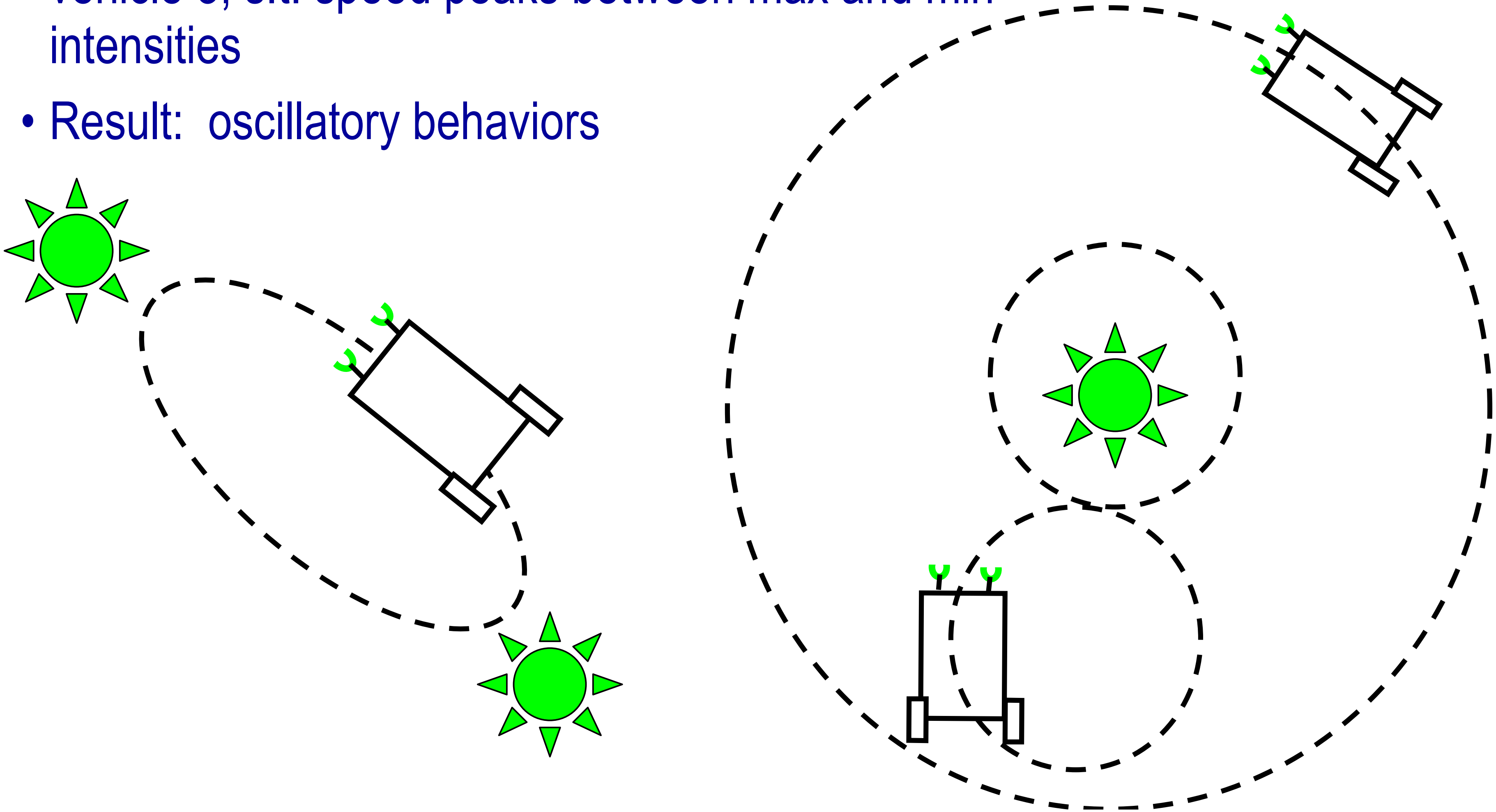
Braitenburg Vehicle 3: “Love and Exploration”

- Two motors, two sensors
- Same as vehicle 2, but with inhibitory connections
- One configuration: approaches and stops at strong light (“love”)
- Second configuration: approaches light, but always exploring (“explorer”)

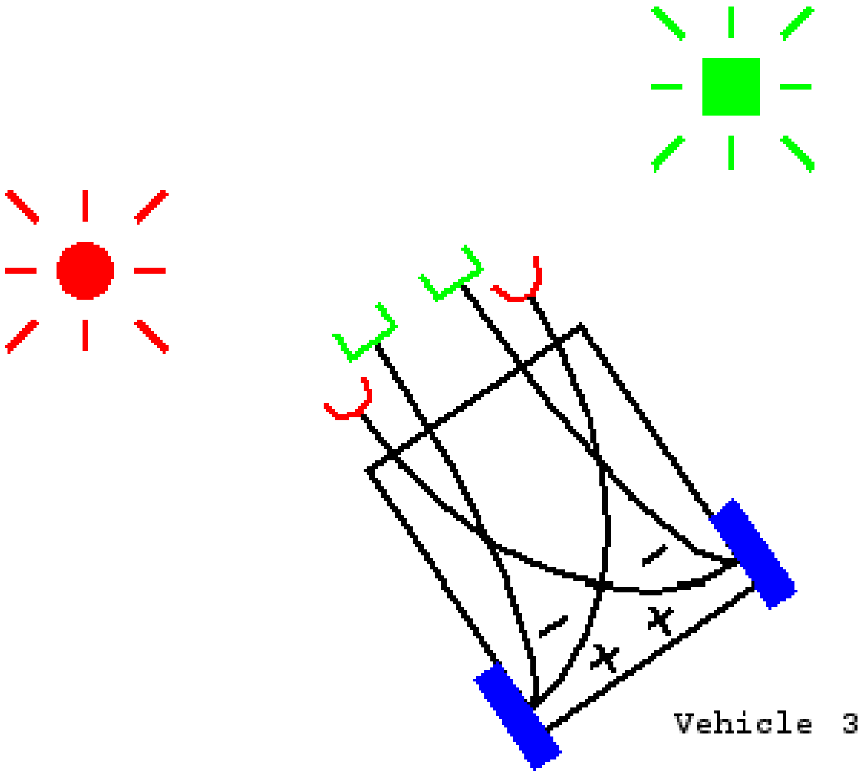


Braitenburg Vehicle 4: “Values and Special Tastes”

- Two motors, two sensors
- Add various non-linear speed dependencies to vehicle 3, s.t. speed peaks between max and min intensities
- Result: oscillatory behaviors



What would you expect of this vehicle?

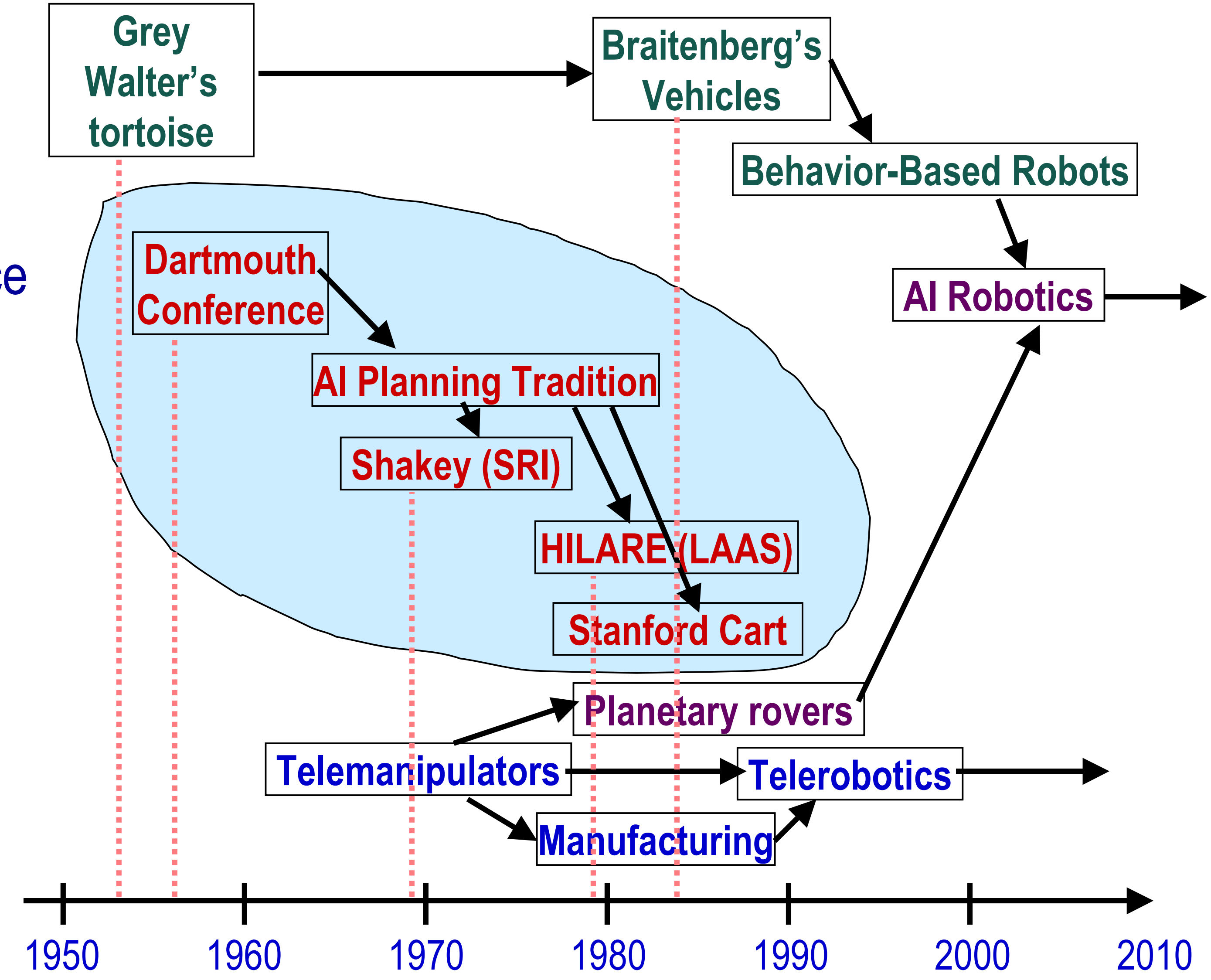


Summary of Braitenberg's Vehicles

- Systems are inflexible, non-reprogrammable
- However, vehicles are compelling in overt behavior
- Achieve seemingly complex behavior from simple sensorimotor transformations

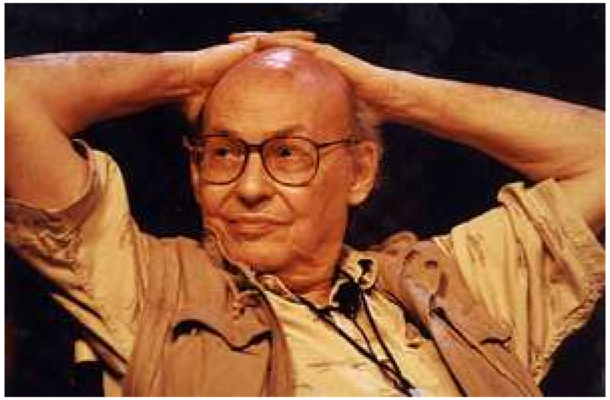
Historical Precursors to Today's Intelligent Robotics

- Cybernetics
- Artificial Intelligence
- Robotics



Artificial Intelligence (AI)

- Beginnings of AI: Dartmouth Summer Research Conference (1955)
- Original topics studied:
  - Language
  - Neural nets
  - Complexity theory
  - Self-improvement
  - Abstractions
  - Creativity



Marvin Minsky, MIT

- Marvin Minsky: *an intelligent machine "would tend to build up within itself an abstract model of the environment in which it is placed. If it were given a problem it could first explore solutions within the internal abstract model of the environment and then attempt external experiments."*

Early AI Roots Strongly Influenced Research

- Through mid-80’s, AI research strongly dependent upon:
  - Representational knowledge
  - Deliberative reasoning methods
  - Hierarchical organization

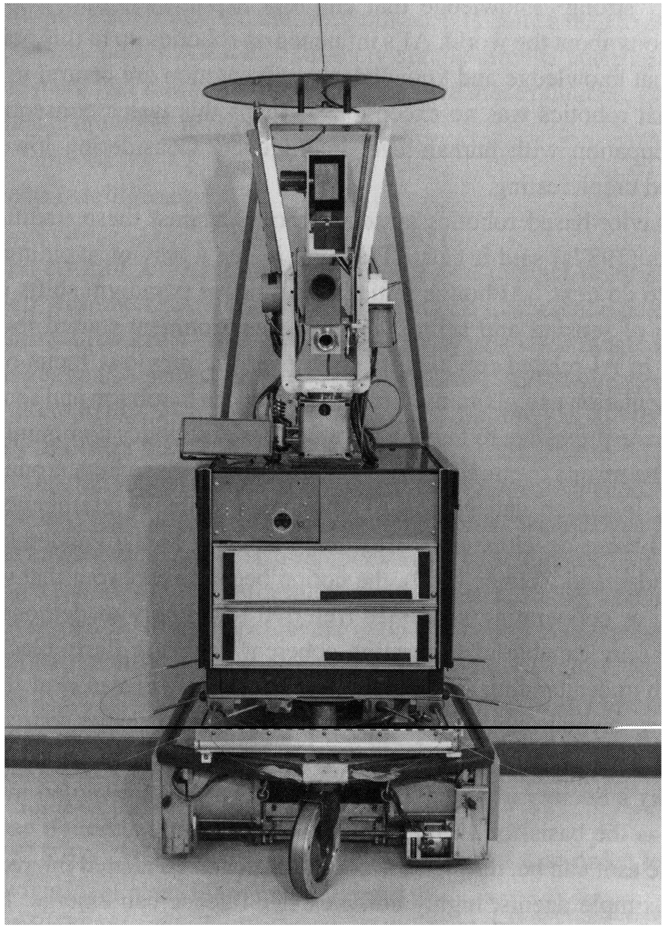
Classical AI Methodology

- Key characteristics:
  - The ability to represent hierarchical structure by abstraction
  - The use of "strong" knowledge using explicit symbolic representation
- Beliefs:
  - Knowledge and knowledge representation are central to intelligence
  - Robotics is no exception
- Focus:
  - Human-level intelligence
- Not of interest:
  - Animal-level intelligence

Early Robotics Development

Shakey (SRI), 1960's

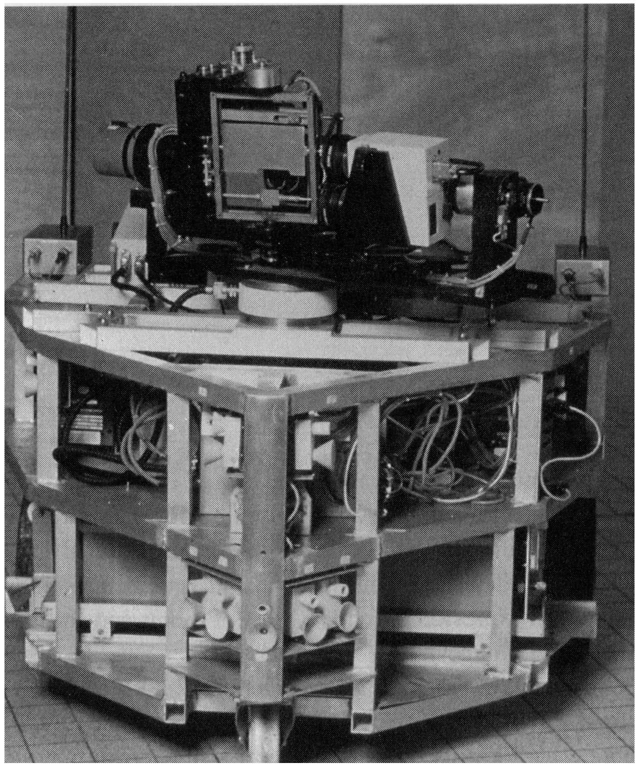
- One of first mobile robots
- Sensors:
  - Vidicon TV camera
  - Optical range finder
  - Whisker bump sensors
- Environment: Office environment with specially colored and shaped objects
- STRIPS planner: developed for this system
  - Used world model to determine what
  - actions robot should take to achieve goals



Early Robotics Development (con't.)

HILARE (LAAS-CNRS), 1970's

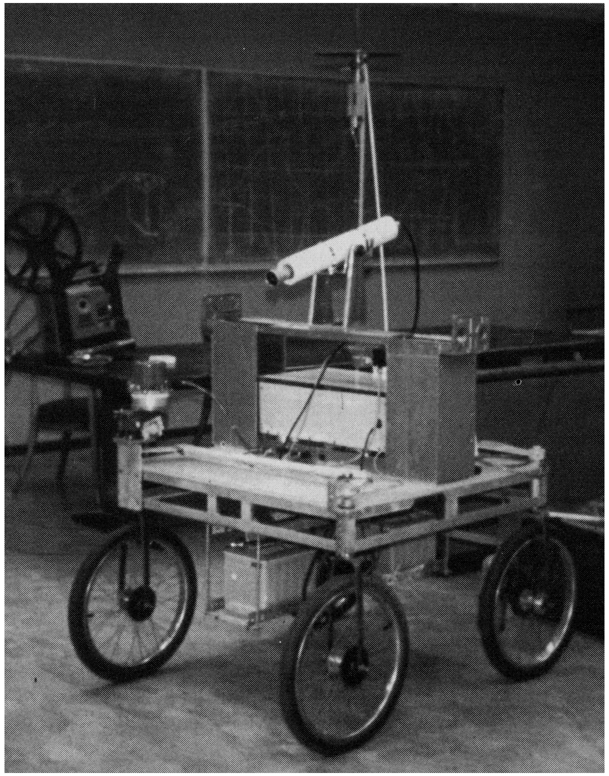
- Sensors: Video camera, 14 sonar, laser range finder
- Three wheels: two drive, one caster
- Weight: 400 kg
- World: smooth floors, office environment
- Planning:
  - Conducted in multi-level geometric representational space
- Use: for experimentation for over a decade



Early Robotics Development (con't.)

Stanford Cart, 1970's (Moravec)

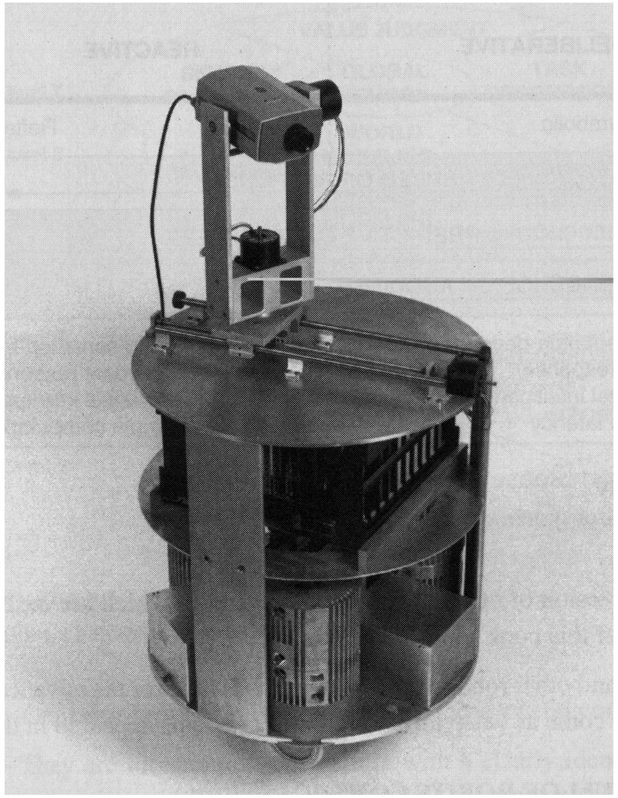
- Sensors: Stereo vision used for navigation
- Speed: Very slow, moving at about 1 meter per 10-15 minutes
- Full run: 5 hours
- Obstacles: added to internal map as enclosing spheres
- Search: Used graph search algorithm to find shortest path
- Accomplishments: Successfully navigated complex 20-meter courses, visually avoiding obstacles



Early Robotics Development (con't.)

CMU Rover, 1980's

- Follow-on to Stanford Cart
- Sensors:
  - Camera mounted on pan/tilt
  - Infrared and sonar sensors
- Actuators: Three independently powered/steered wheels
- Accomplishments: Set stage for upcoming behavior-based robotics



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
  - 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

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

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

Use Rules of Inference, Unification to Prove Theorems

- Rules of inference:
  - P and $\sim P \vee Q$ resolves to Q (modus ponens)
  - $P \vee Q$ and $\sim P \vee Q$ resolves to Q
  - $P \vee Q$ and $\sim P \vee \sim Q$ resolves to $Q \vee \sim Q$ and $P \vee \sim P$
  - $\sim P$ and P resolves to Nil
  - Etc.

- Unification:
  - Finding substitutions of terms for variables to make expressions identical
  - Equivalent to symbolic pattern matching
    - E.g.: Add-List: ON(x,y) can be made equivalent to ON(A,B) through substitution and unification

Many AI Planners Developed From these Concepts

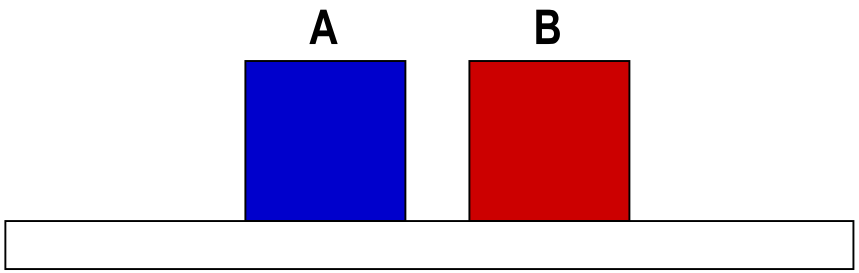
- Well-known AI Planners:
  - STRIPS (Fikes and Nilsson, 1971): theorem-proving system
  - ABSTRIPS (Sacerdoti, 1974): added hierarchy of abstractions
  - HACKER (Sussman, 1975): use library of procedures to plan
  - NOAH (Sacerdoti, 1975): problem decomposition and plan reordering

STRIPS-Based Approach to Robot Control

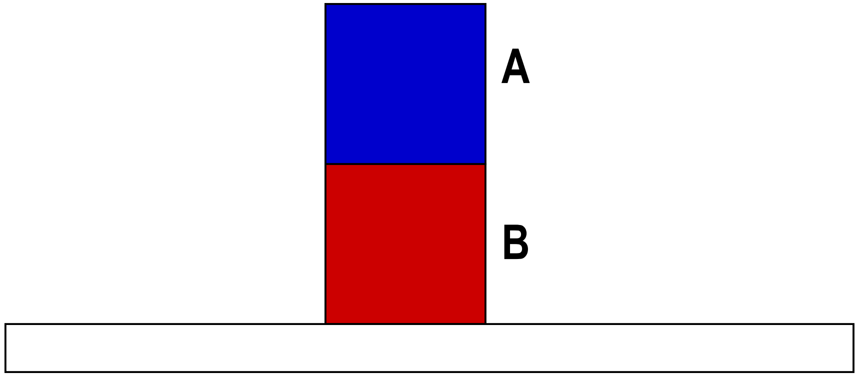
- Use first-order logic and theorem proving to plan strategies from start state to goal
- Define:
  - Goal State
  - Initial State
  - Operators
- STRIPS Operators have:
  - Action description
  - Preconditions
  - Effect:
    - Add-list
    - Delete-list

Simple Example of STRIPS-Style Planning

- 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)

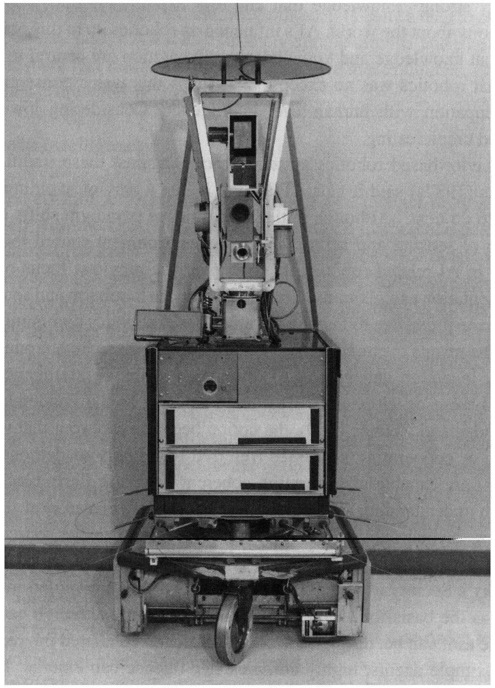
    At(b,x)

    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)

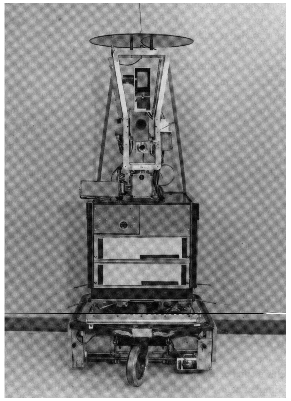
    EFFECT: On(Shakey,b)

  - Climb down from rigid objects:

    (etc.)

  - Turn light switches on and off:

    (etc.)



Challenges of AI and Planning Systems

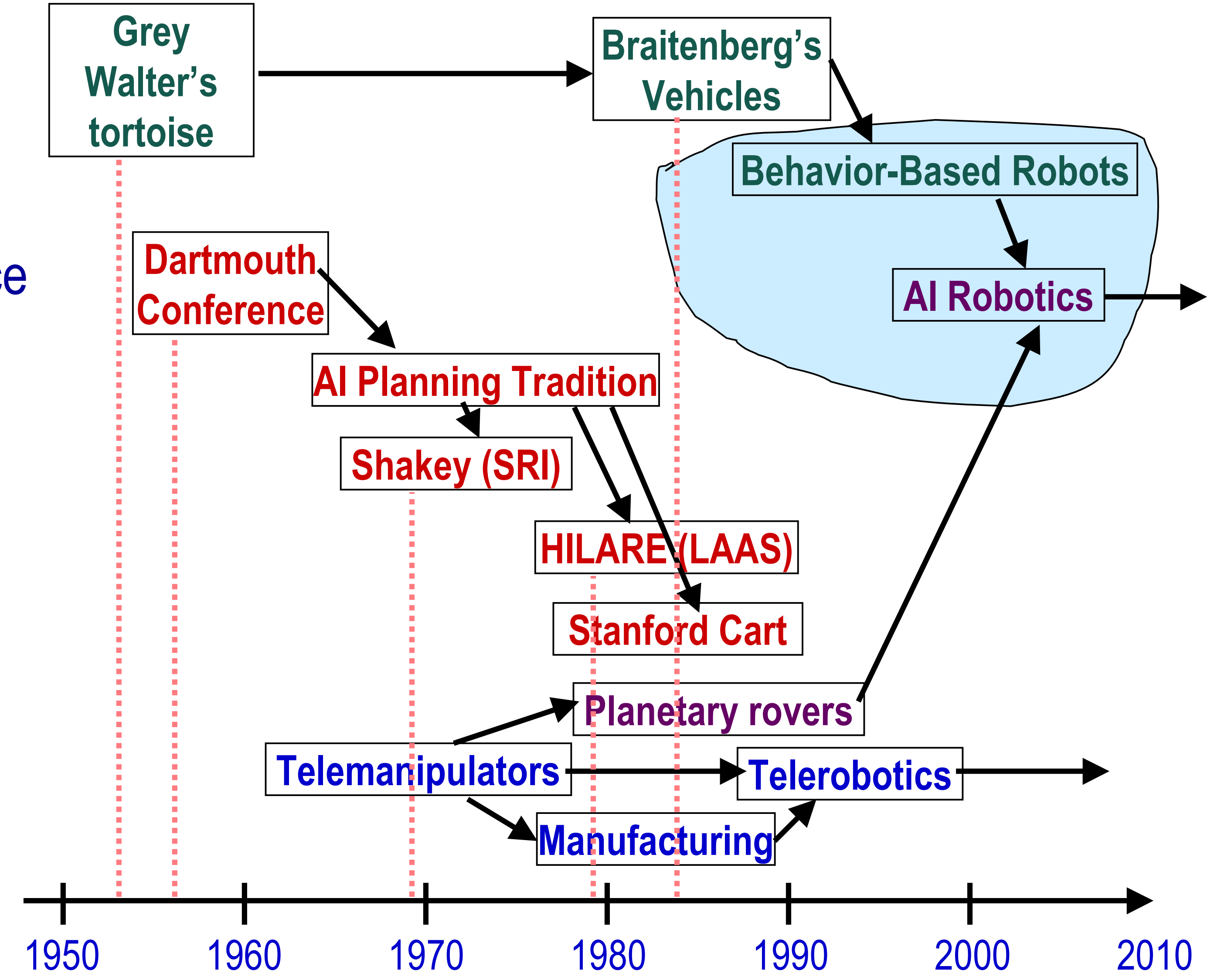
- Closed world assumption: *Assumes that world model contains everything the robot needs to know: there can be no surprises*

- *Frame problem:* How to represent real-world situations in a manner that is computationally tractable

- *Open world assumption:* means that the closed world assumption cannot apply to the given domain

Historical Precursors to Today's Intelligent Robotics

- Cybernetics
- Artificial Intelligence
- Robotics



Behavior-Based Robotics' Response to Classical AI

- Reacted against classical AI
- Brooks (1987-1990):

  "Planning is just a way of avoiding figuring out what to do next"

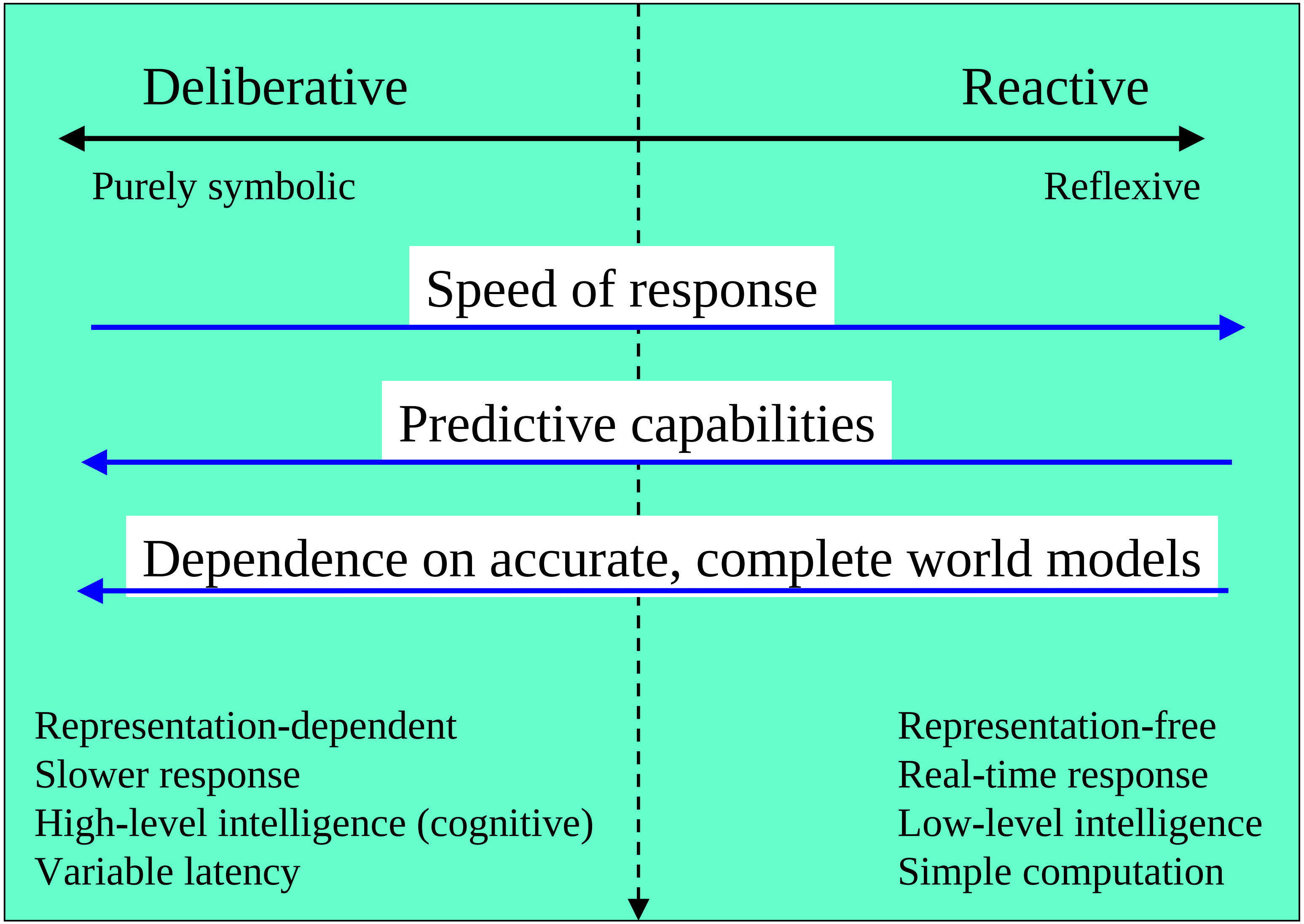
  "Elephants don't play chess"

- Increased emphasis on:
  - Sensing and acting within environment
- Reduced emphasis on:
  - Knowledge representation
  - Planning

Rodney Brooks, MIT, with Cog

Now typically called "New AI"

Wide Spectrum of Robot Control



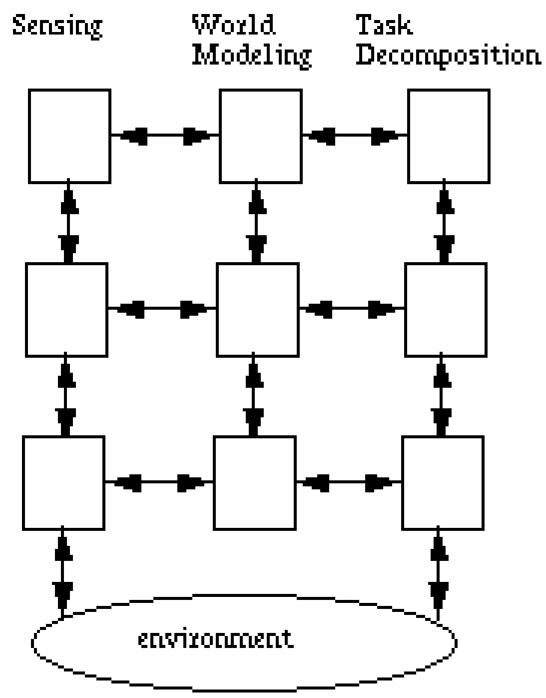
Deliberative Control

- Common characteristics:
  - Hierarchical in structure
  - Clearly identifiable division of functionality
  - Communication and control is predictable and predetermined
  - Higher levels provide subgoals for lower levels
  - Planning scope changes with descent in hierarchy
  - Heavy reliance on symbolic representations

- Seemingly well-suited for structured and highly predictable environments (e.g., manufacturing)

Example Deliberative Architecture: NASREM

- NASREM: NASA Standard Reference Model for Telerobots
- Developed by Albus, mid-80's
- Multiple layers
- Each layer has:
  - Sensory processing
  - World modeling
  - Task decomposition
  - Value judgement
- All layers joined by global memory through which representational knowledge is shared
- Perception is not tied directly to action



NASREM

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

Other Deliberative Architectures

- RCS (Real-time Control System): similar to NASREM
- Drexel University's Nested hierarchical intelligent controller
- RPI model: restricted to 3 layers -- organization, coordination, and execution

Drawbacks to Deliberative Control led to Reactive Control

- Shortcomings:
  - Lack of responsiveness in unstructured and uncertain environments, due to:
    - Requirements of world modeling
    - Limited communication pathways
  - Difficulty of engineering complete systems incrementally

Reactive Control

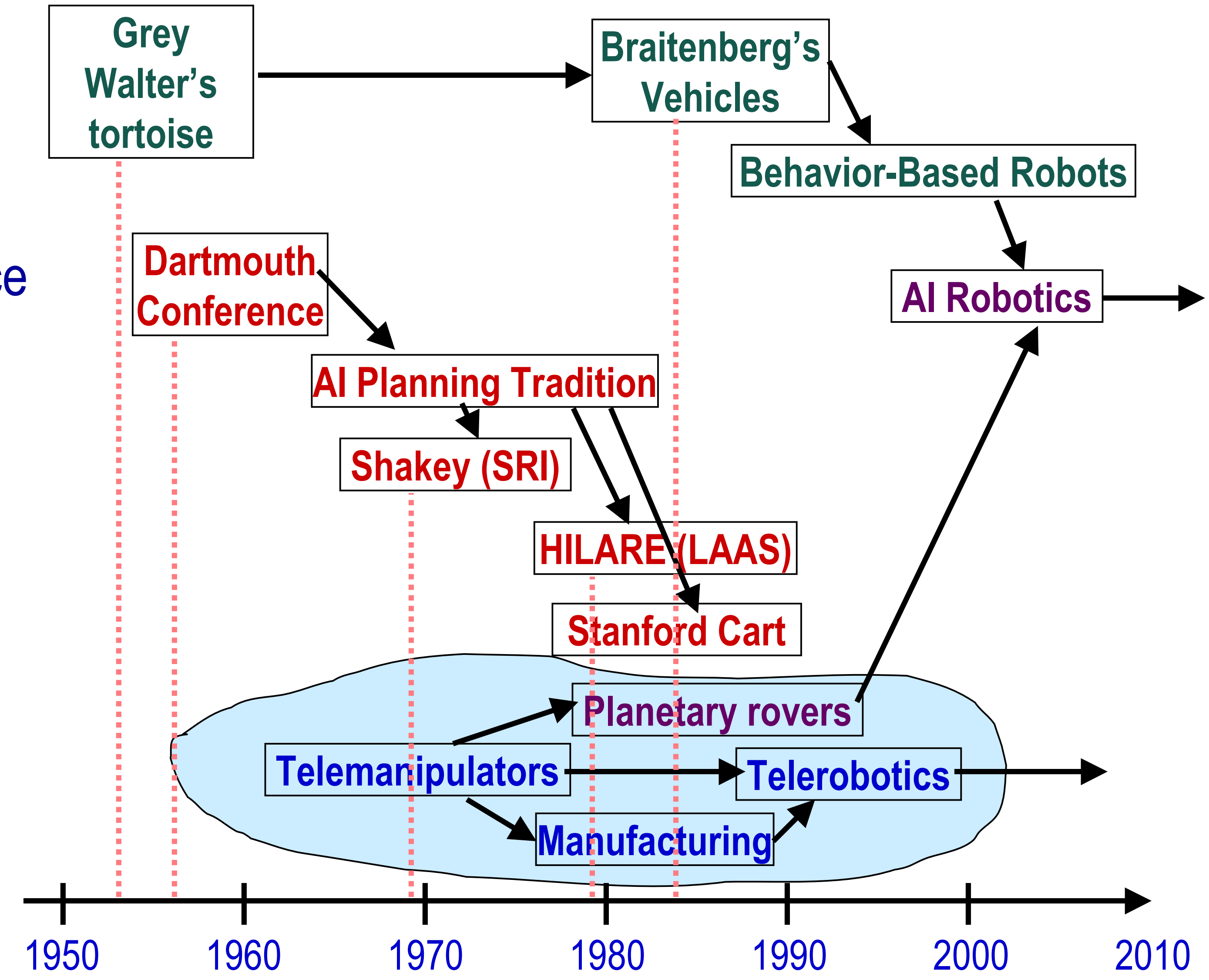
- Definition: a technique for tightly coupling perception and action, typically in the context of motor behaviors, to produce timely robotic response in dynamic and unstructured worlds.
- *Individual behavior*: a stimulus/response pair for a given environmental setting that is modulated by attention and determined by intention
- *Attention:* prioritizes tasks and focuses sensory resources; determined by current environmental context
- *Intention:* determines set of behaviors that should be active based on internal goals and objectives
- *Overt or emergent behavior*: the global behavior of robot as consequence of interaction of active individual behaviors
- *Reflexive behavior*: behavior generated by hardwired reactive behaviors with tight sensor-effector loop, using no world models

Key Issues of Behavior-Based Control

- Situatedness: robot operates in the real world
- Embodiment: robot has a physical presence (body)
- Emergence: Intelligence arises from interaction of robot with environment
- Grounding in reality: avoid symbol grounding problem
- Ecological dynamics: cannot characterize environment
- Scalability: Unknown whether behavior-based control will scale to human-level intelligence

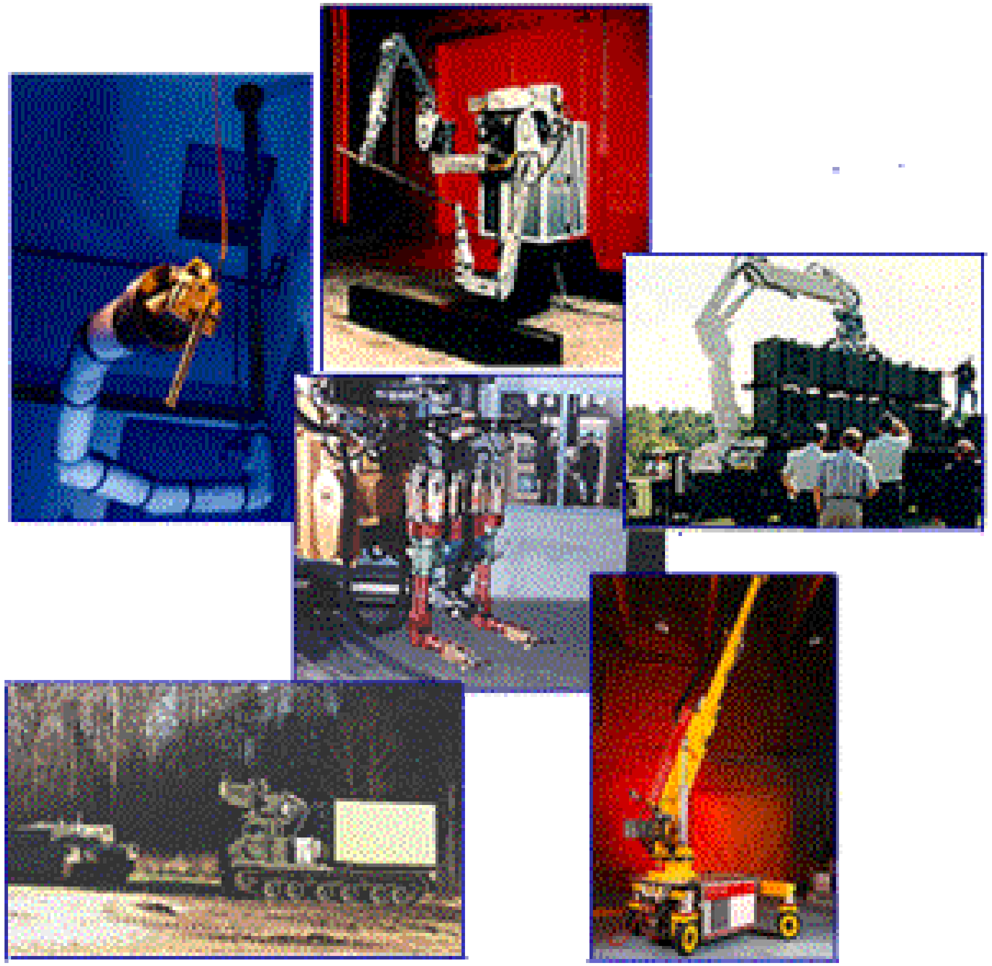
Historical Precursors to Today's Intelligent Robotics

- Cybernetics
- Artificial Intelligence
- Robotics



Telemanipulators and Telerobotics

- Teleoperation: human operator controls robot remotely through mechanical or electronic linkages
- Operator and robot:
  - Leader/follower relationship
  - Human leads, robot mimics human behaviors
- Issues include:
  - Force feedback
  - Operator telepresence
  - Supervisory control
- Challenges:
  - Operator overload
  - Cognitive fatigue
  - Simulator sickness



ORNL Telemanipulator Projects

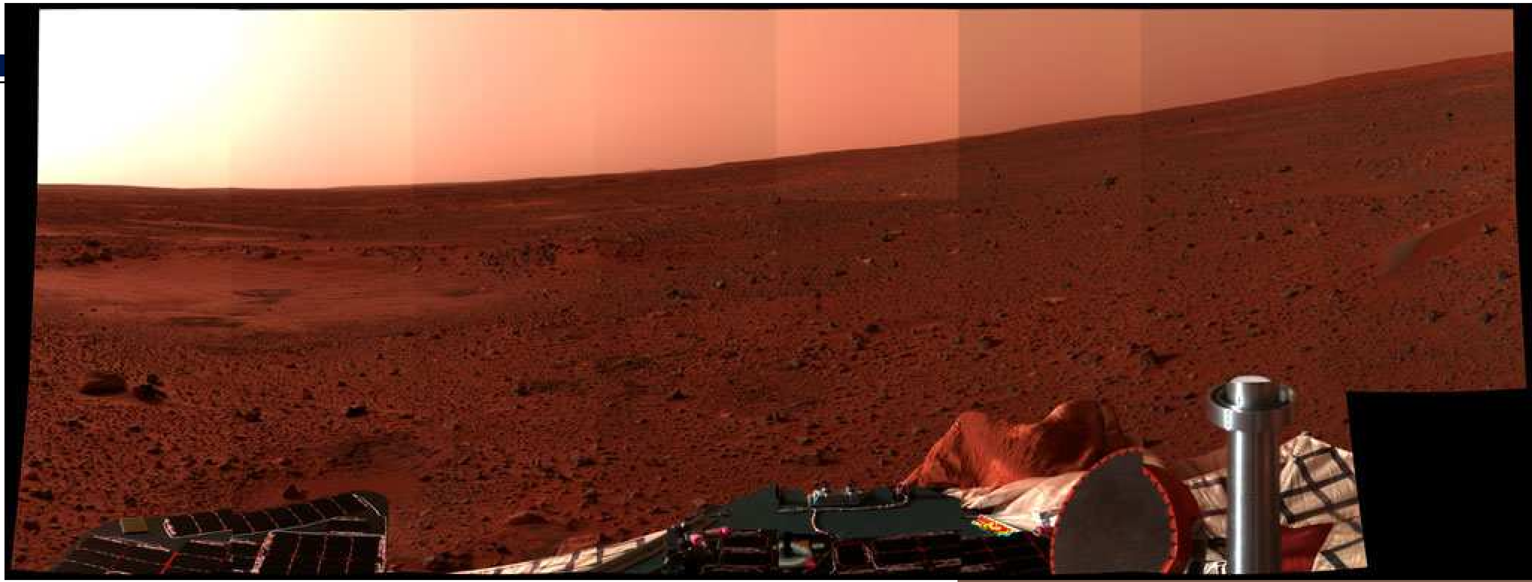
Space Robotics

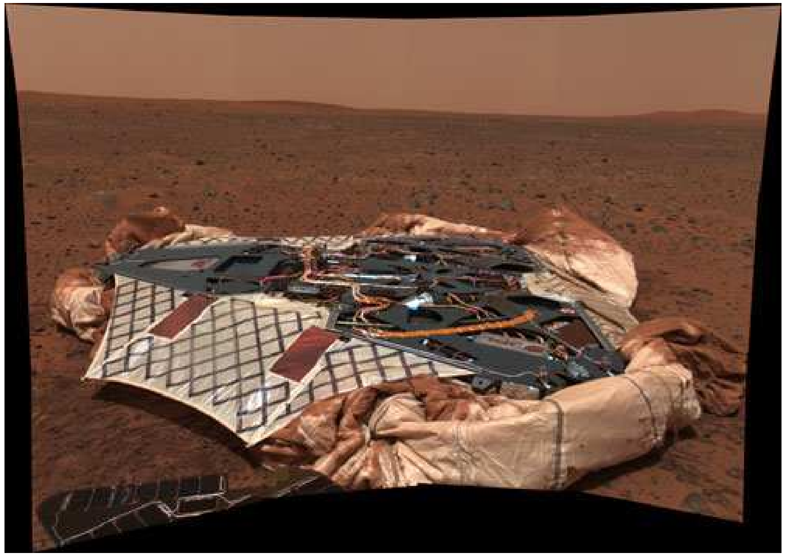
- Planetary rovers:
  - One-of-a-kind
  - Significant consequences of failure

- Sojourner robot:
  - Part of PathFinder Mars Mission
  - Very successful robot
  - Explored MARS from July 5 – Sept. 27, 1997
  - Fully teleoperated

Sojourner Robot on Mars

Current Robots on Mars: *Opportunity* and *Spirit*





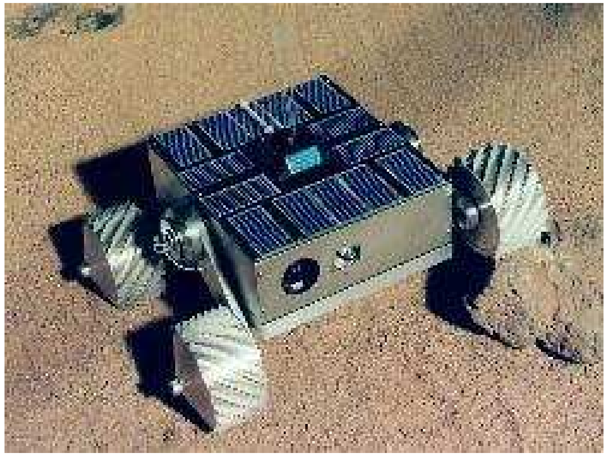
Lander

Rover

Landed on Mars in January 2004 – still operational!

Eventually, Space Robotics May Move More Toward Intelligent Robotics

Challenge: Proving capabilities of autonomous systems



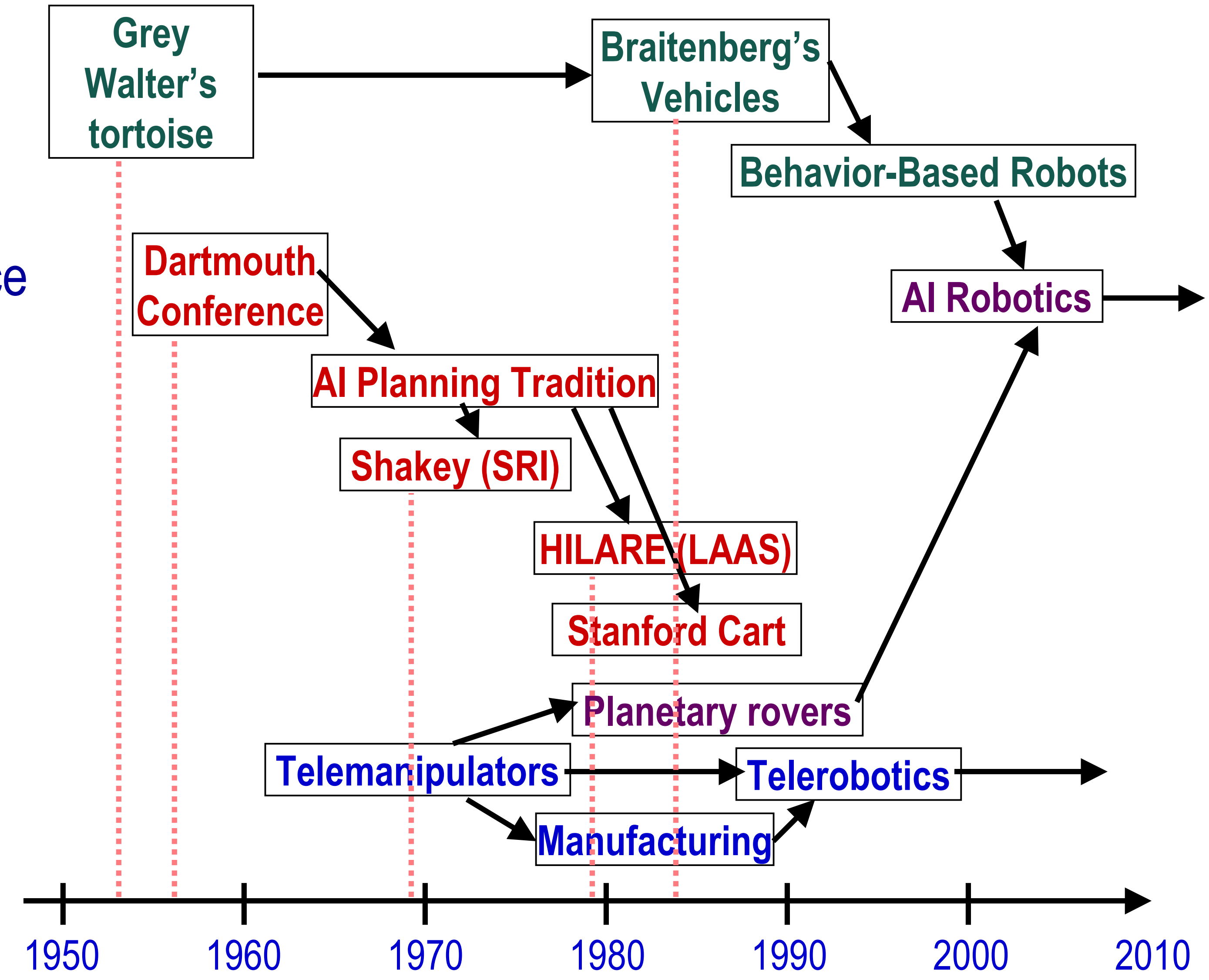
Nanorover, prototype for comet mission

Rocky 7, with stereo vision and sampling manipulator

Gofer, with active center of gravity compensation

Historical Precursors to Today's Intelligent Robotics

- Cybernetics
- Artificial Intelligence
- Robotics



Summary

- Many threads of robotics-related research:
  - Cybernetics
  - Artificial intelligence
  - Intelligent robot precursors

- Primary ongoing directions:
  - Intelligent (AI) robotics
  - Telerobotics
  - Space robotics