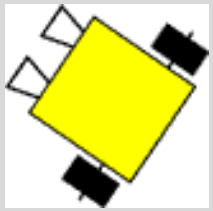
Unit E

Control Architectures

Exploring Robotics

Spring, 2013

Joel Kammet
Brooklyn College
CUNY



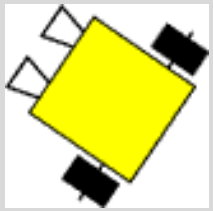
Control Systems

Control theory:

a branch of engineering involving the mathematical study of automated control systems.

Automated control systems include

- industrial processes (assembly lines, etc.)
- airplanes
- nuclear power plants
- robots
- ...



Joel Kammet
Brooklyn College
CUNY

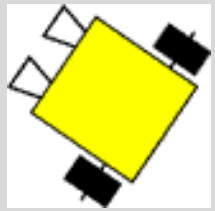
Goal States

A *goal state* is

- the desired state of the system
- where, or in what condition, the system wants to be

Goal states include

- achievement goals
- maintenance goals



Joel Kammet
Brooklyn College
CUNY

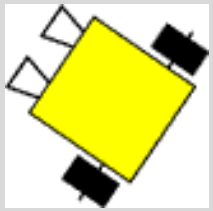
Achievement and Maintenance Goals

Achievement goals:

- attain some measure of performance
- arrive at a destination
- complete a task

Maintenance goals:

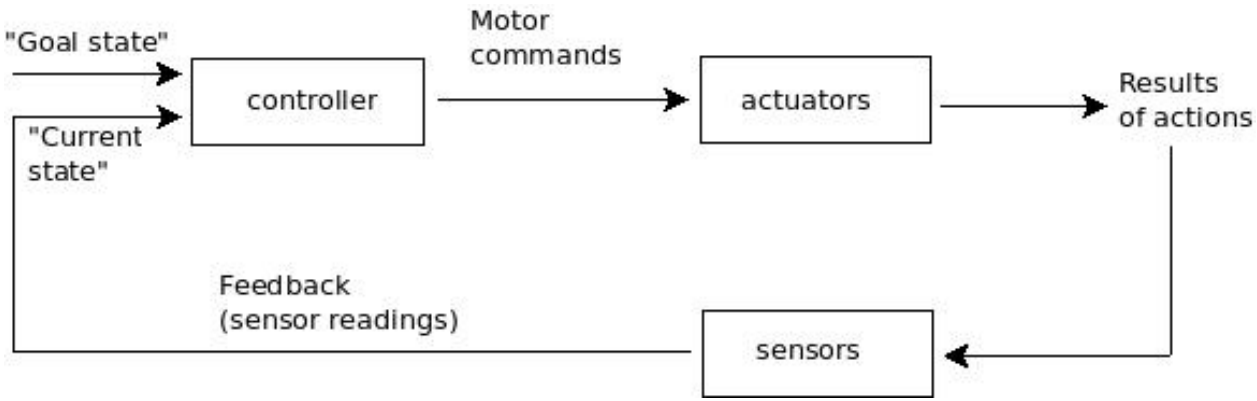
- keep some parameter (measure of performance) within a predetermined allowable range
- stay on road
- remain upright and balanced

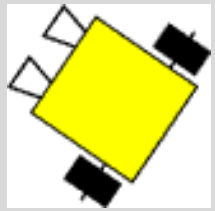


Joel Kammet
Brooklyn College
CUNY

Feedback Control

A closed-loop control system:



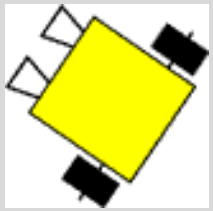


Joel Kammet
Brooklyn College
CUNY

Types of Feedback Control

Output signals (motor commands) are adjusted based on the difference (error) between current state and goal state.

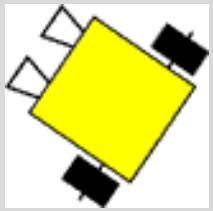
- proportional control
  - output is adjusted in proportion to the amount of error
  - the bigger the error, the greater the adjustment
  - $o(t) = K_p e(t)$
- derivative control
  - output is adjusted in proportion to the rate of change of error
  - if error is decreasing rapidly, reduce the adjustment
  - $o(t) = K_d \frac{d}{dt} e(t)$
- integral control
  - output is adjusted in proportion to the duration of error
  - if error persists for a long time, increase the adjustment
  - $o(t) = K_i \int_0^t e(\tau) d\tau$



Joel Kammet
Brooklyn College
CUNY

Combining Feedback Control Signals

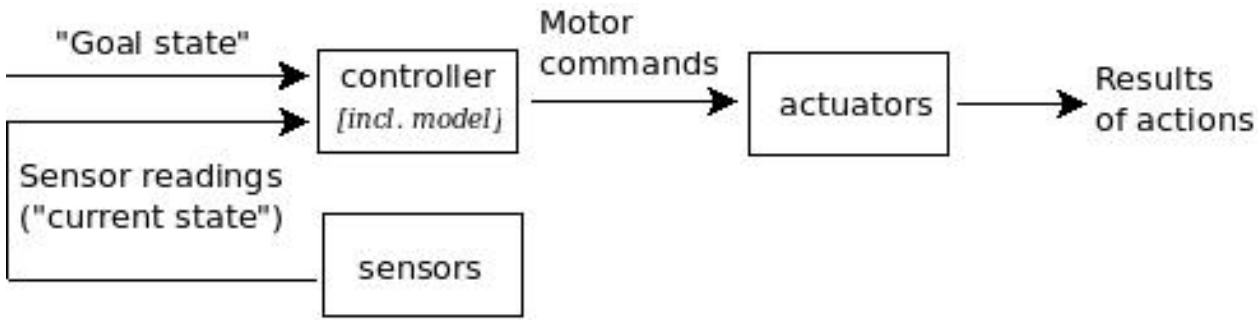
- PD Control
  - Combines proportional and derivative control
  - $o(t) = K_p e(t) + K_d \frac{d}{dt} e(t)$
- PID Control
  - Combines proportional, integral and derivative control
  - $o(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$

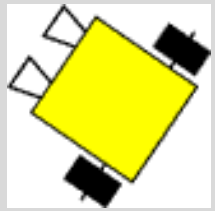


Joel Kammet
Brooklyn College
CUNY

Feedforward Control

An open-loop control system:





Joel Kammet
Brooklyn College
CUNY

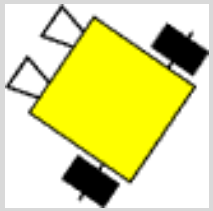
Control Architectures

A control architecture is

the set of principles (i.e., tools, rules, styles, guidelines ...) for organizing a control system

Categories of robot control architectures:

- Deliberative control
- Reactive control
- Hybrid control
- Behavior-based control



Joel Kammet
Brooklyn College
CUNY

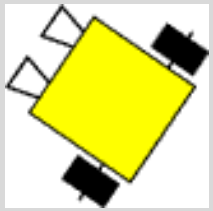
Differences Among Control Architectures

- Modularity

  how control program is broken down
- Time-scale

  immediate real-time response vs. long-range plan
- Representation

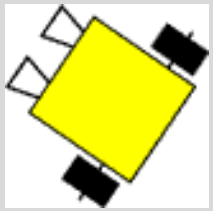
  how robot “envisions” its world



Joel Kammet
Brooklyn College
CUNY

Considerations for Choice of Architecture

- sensor noise
- actuator noise
- static or dynamic environment
- fully- or partially-observable environment
- speed at which sensors react
- speed at which controller and effectors react
- need to remember past events/conditions
- need to predict future events/conditions
- need to learn (to improve behavior)



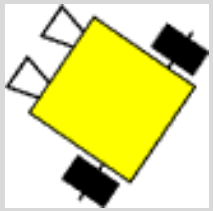
Joel Kammet
Brooklyn College
CUNY

World Model

A world model is

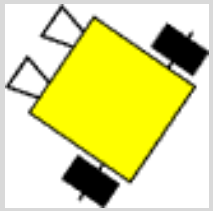
a simplified, abstract description of its environment:

- "map" of the world
- its own possible actions
- expected or possible consequences of actions
- expected or possible changes in environment
- its tasks or goals
- physical "laws"
- sensor readings/motor commands (sensorimotor state)
- contents of its memory
  - values of variables
  - remembered facts
  - predictions



Joel Kammet
Brooklyn College
CUNY

Representation



Representation is

what information is stored and how it is encoded

- detailed measurements/“pictures”
- landmarks
- sensor readings
- history of events, actions, consequences

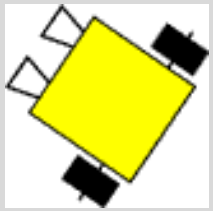
Joel Kammet
Brooklyn College
CUNY

Representation

Representation is

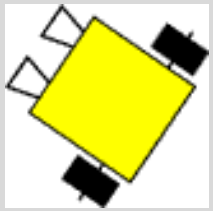
what information is stored and how it is encoded

- detailed measurements/“pictures”
- landmarks
- sensor readings
- history of events, actions, consequences
- lookup tables of transition rules
- graph illustrating transition rules



Joel Kammet
Brooklyn College
CUNY

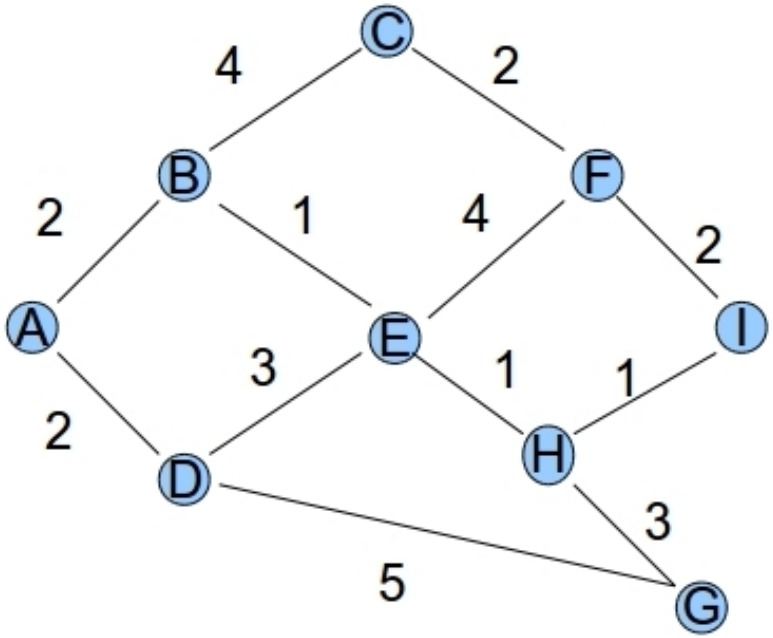
Any questions?



Joel Kammet
Brooklyn College
CUNY

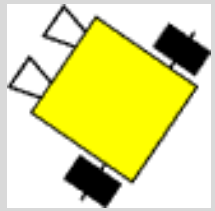
Two different representations of a map

A	B	C
D	E	F
G	H	I



Representation is

- what information is stored
- how it is encoded

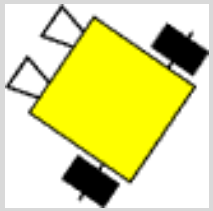


Joel Kammet
Brooklyn College
CUNY

Next time...

How a world model and representation are used in actual control architectures:

- Deliberative control (chapter 13)
- Reactive control (chapter 14)



Joel Kammet
Brooklyn College
CUNY

Conditionals

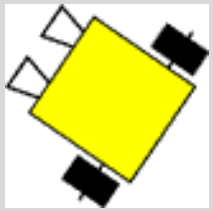
A boolean expression is

an expression that has only two possible values:
true or **false**

A conditional statement is

a statement in the form
“if [predicate] then [consequent]”

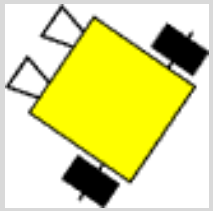
(The predicate is a *boolean expression*.)



Joel Kammet
Brooklyn College
CUNY

Deliberative Control

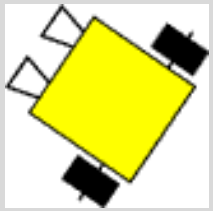
- Sense, model, plan, act
- Search through alternative possible sequences of actions for
  - success
  - optimality
  - approximation/compromise



Joel Kammet
Brooklyn College
CUNY

Planning: Requirements

- time
- space
- information
- plan must remain accurate
- must maintain awareness of state
- accuracy of effectors



Joel Kammet
Brooklyn College
CUNY

Intractability

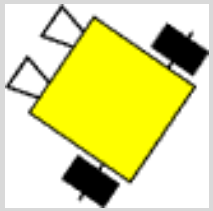
Intractable means

highly complex; difficult to solve.

(Sensor/state space grows exponentially.)

Other obstacles:

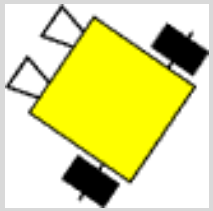
- dynamic environment
- not fully observable
- noise



Joel Kammet
Brooklyn College
CUNY

Reactive Control

- Reflex action
- Sense $\longrightarrow$ act
- Action selection
  - Mutually exclusive conditions
  - Command arbitration (choose one out of several commands)
  - Command fusion (combine multiple commands into one)

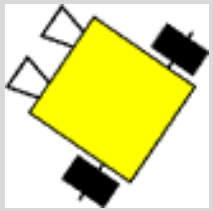


Joel Kammet
Brooklyn College
CUNY

Reactive Control Examples

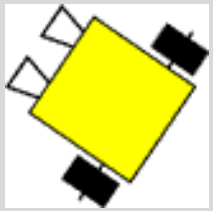
Example (RCX line-following)

- threshold 1 = 41
- threshold 2 = 37
- rule 1: sensor reading $\leq$ threshold 1 stop right motor, fwd left motor
- rule 2: sensor reading $\leq$ threshold 2 reverse right motor, fwd left motor
- rule 3: otherwise stop left motor, fwd right motor



Joel Kammet
Brooklyn College
CUNY

Reactive Control Examples

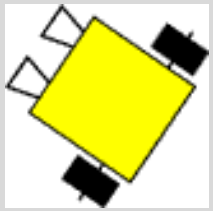


Example (simple navigation)

- rule 1: facing red wall turn right
- rule 2: facing blue wall turn left
- rule 3: facing treasure stop
- rule 4: otherwise go straight ahead

Joel Kammet
Brooklyn College
CUNY

Subsumption Architecture



Subsume (according to Merriam-Webster) means:

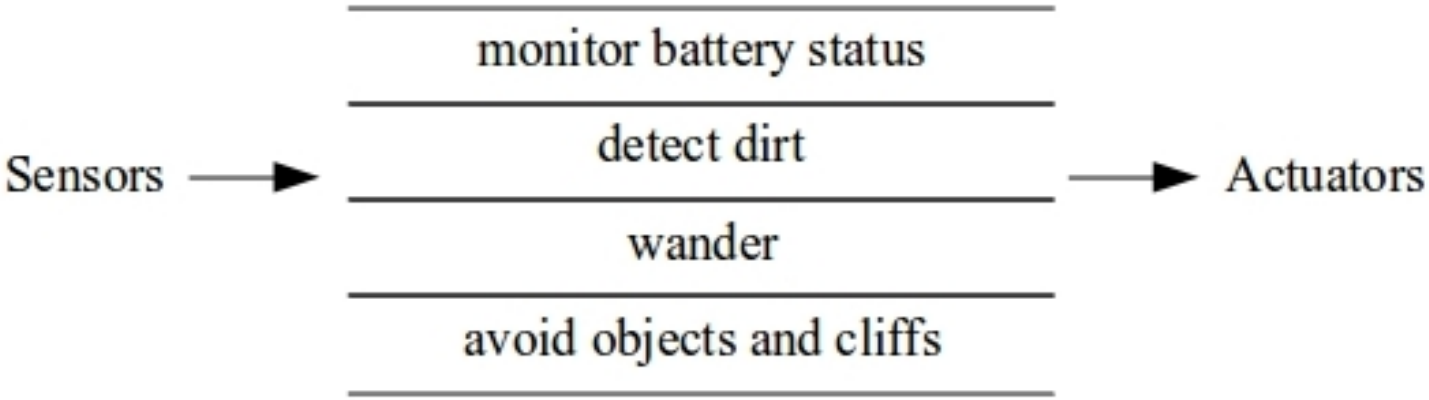
to include or place within something larger or more comprehensive; encompass as a subordinate or component element. e.g.: Red, green, and yellow are subsumed under the term “color”.

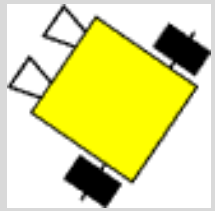
Subsumption Architecture (Rodney Brooks, 1985)

- “layered”, bottom-up design
- capabilities added incrementally
- inspired by biology
- higher layers use lower layers to help achieve their goals
- higher layers can suppress or inhibit lower layers

Joel Kammet
Brooklyn College
CUNY

Subsumption Architecture - Example





Joel Kammet
Brooklyn College
CUNY

Behavior-Based Control

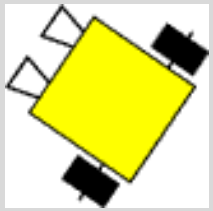
- layered design similar to that of reactive control

  but:

- modules of a reactive control architecture produce simple actions

  whereas

- modules of a behavior-based control architecture produce *behaviors*

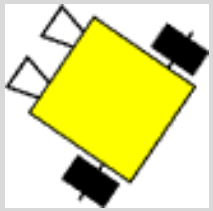


Joel Kammet
Brooklyn College
CUNY

Behavior

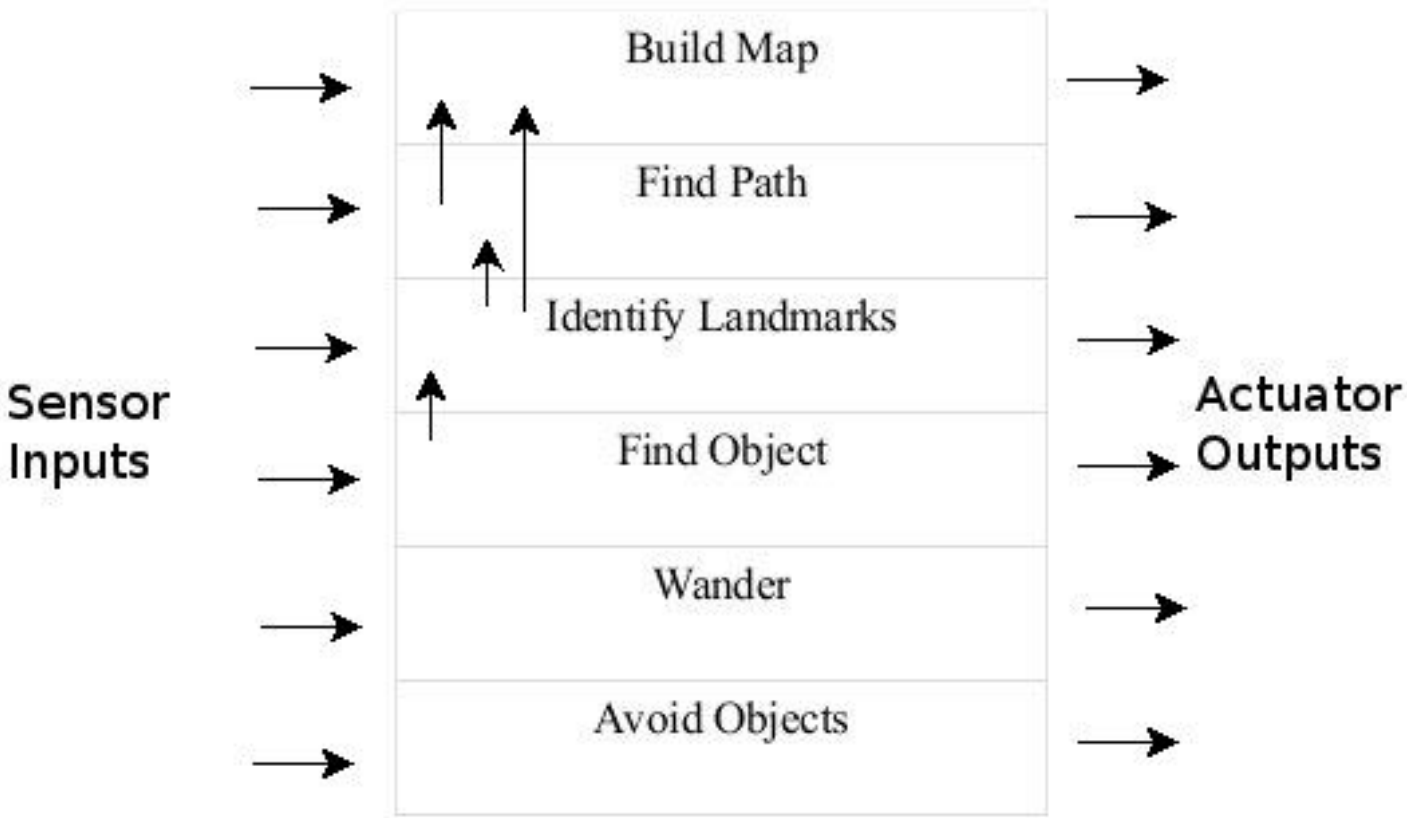
Characteristics of *behaviors*:

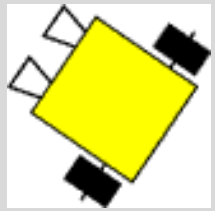
- more complex than the simple actions of reactive control
- behaviors maintain or achieve specific goals
- behaviors are *time-extended*
- behaviors can take input not only from sensors but also from other behaviors
- behaviors can send output to other behaviors as well as to actuators



Joel Kammet
Brooklyn College
CUNY

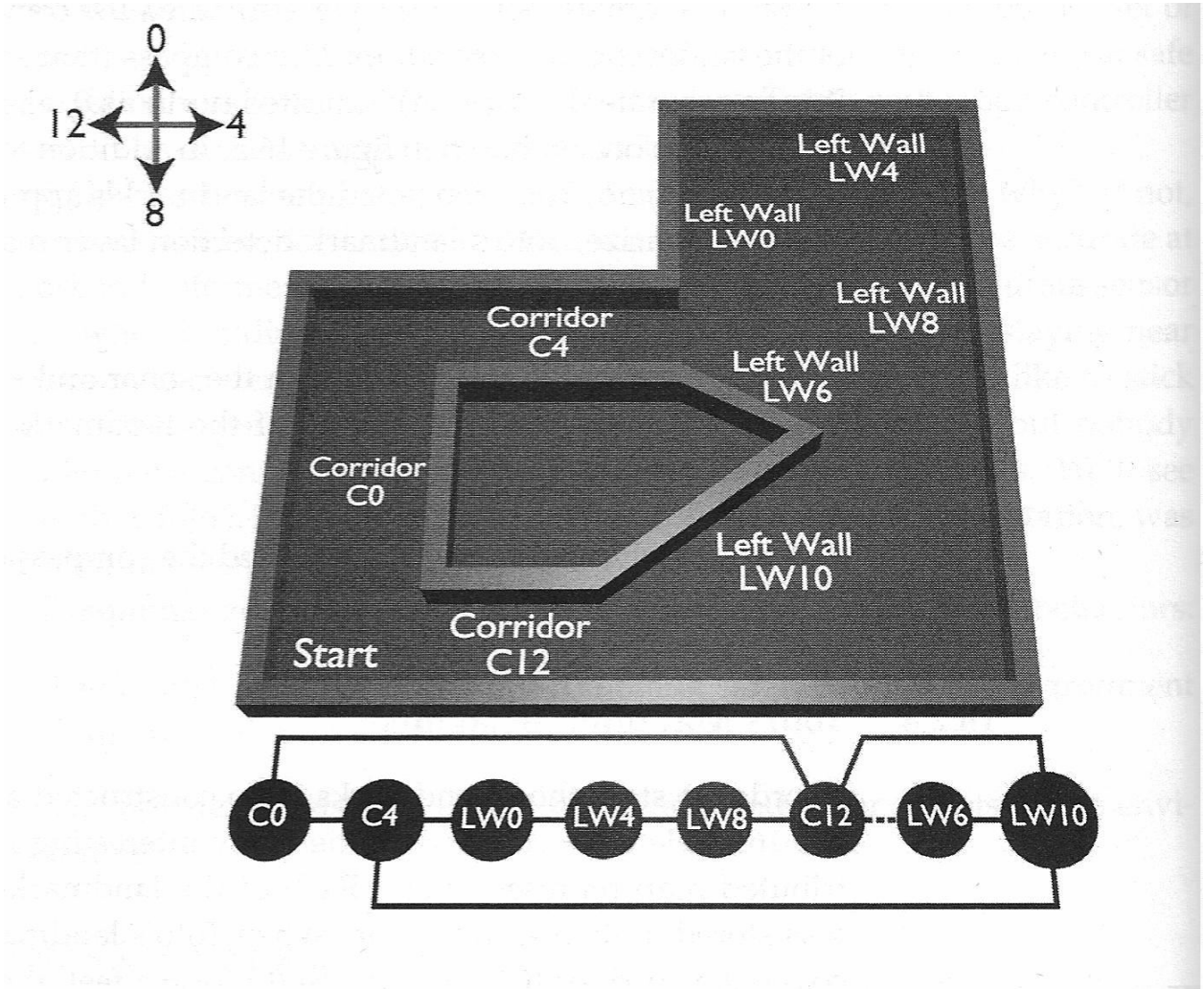
Behavior-based Architecture - Example





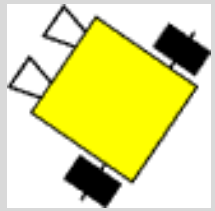
Joel Kammet
Brooklyn College
CUNY

Behavior-based Mapping Application



Toto's environment

source: The Robotics Primer, Maja J. Mataric

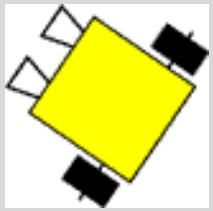


Joel Kammet
Brooklyn College
CUNY

Behavior-based Mapping Application (cont'd)

Toto's Mapping Behavior Attributes (Variables)

- Behavior-type
- Compass-direction
- Approximate-location
- Approximate-length
- Active-status (true/false)
- Goal-status (true/false)
- Most-recent-message-distance
- Most-recent-message-source



Joel Kammet
Brooklyn College
CUNY

What Is Emergent Behavior?

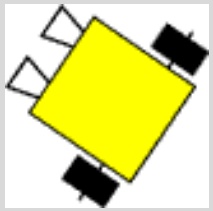
"The whole is greater than the sum of its parts."

A "naive" definition

~~Unexpected behavior that results from interaction between the system and its environment.~~

A better definition

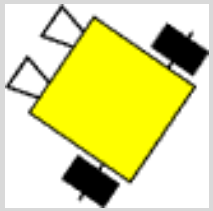
Emergent behavior is a pattern of behavior that results from interaction between the system and its environment and is apparent from an observer's viewpoint but not from the from the controller's (internal) viewpoint.



Joel Kammet
Brooklyn College
CUNY

Emergent Behavior - Examples

- wall following (with no model of a “wall”)
- flocking (with no model of a “flock”)
- ants’ paths converging towards food



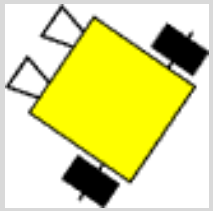
Joel Kammet
Brooklyn College
CUNY

Emergence and Surprise

Can you think of other examples of emergence in nature?

Can surprise be predictable?

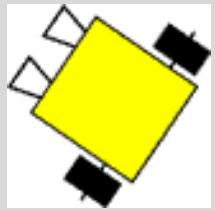
Is surprise necessary for emergence?



Joel Kammet
Brooklyn College
CUNY

Autonomous Mental Development

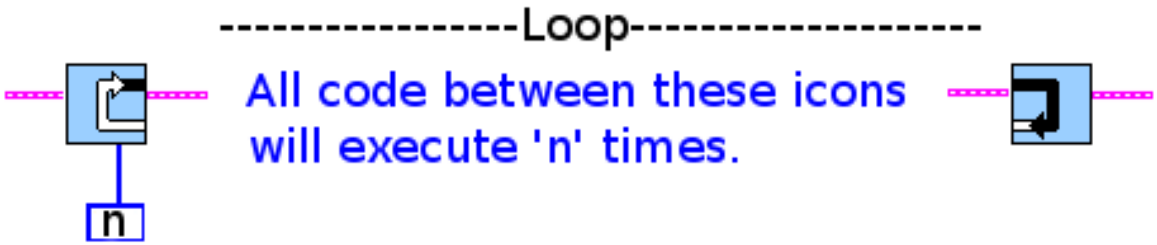
DIFFERENCES BETWEEN ROBOT PROGRAMS		
Properties	**Traditional**	**Developmental**
Not task specific	No	Yes
Tasks are unknown	No	Yes
Generates a representation of an unknown task	No	Yes
Animal-like online learning	No	Yes
Open-ended learning	No	Yes



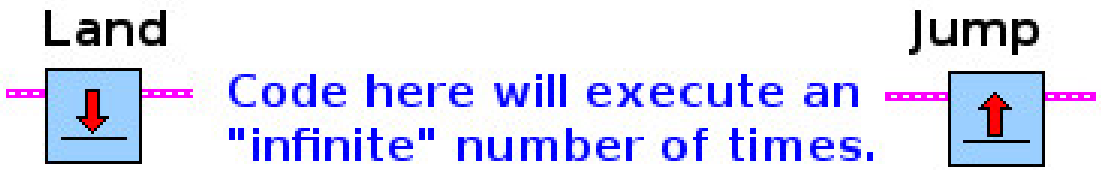
Joel Kammet
Brooklyn College
CUNY

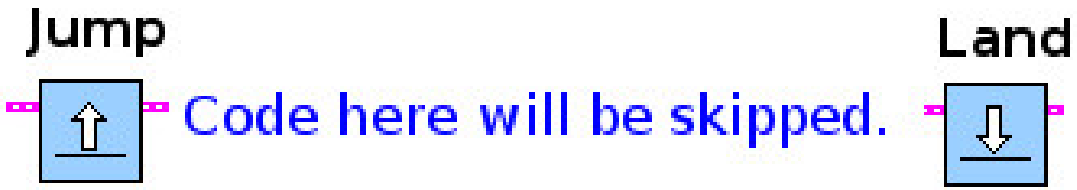
Loops and Jumps

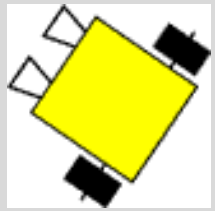
Conditional:



Unconditional:



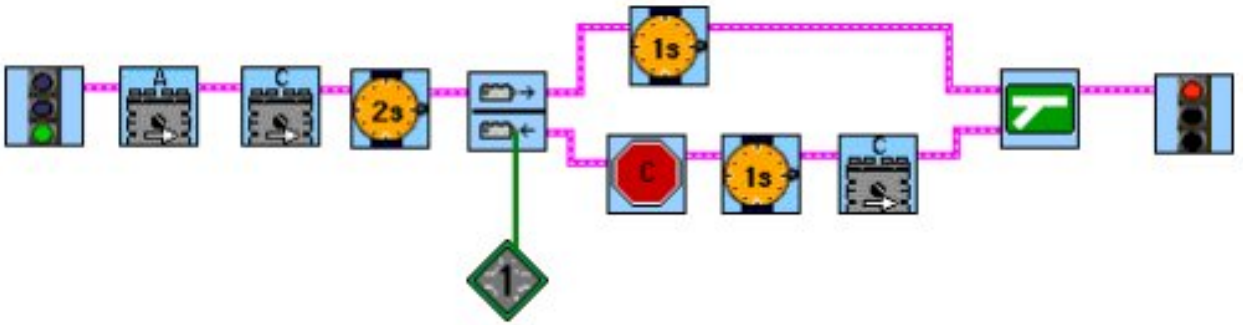




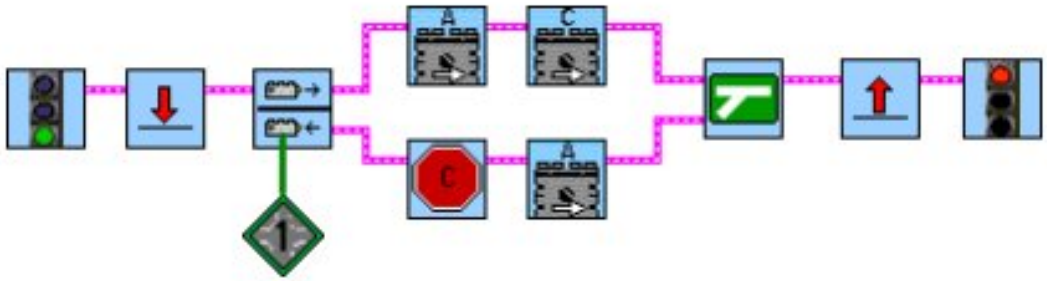
Joel Kammet
Brooklyn College
CUNY

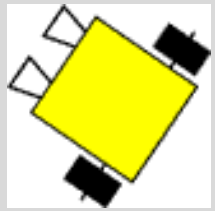
Conditional Branch: Touch Sensor Fork

Not so useful:



Much better:

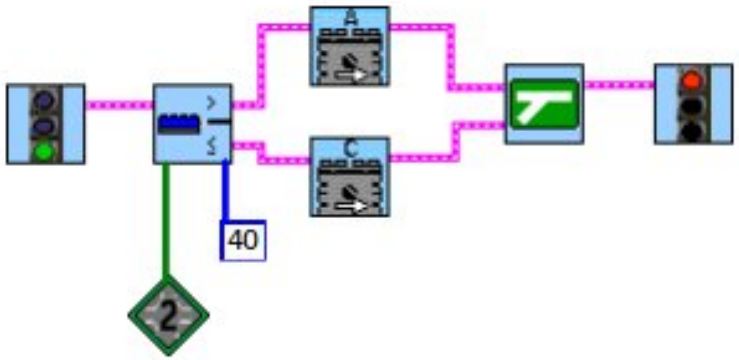




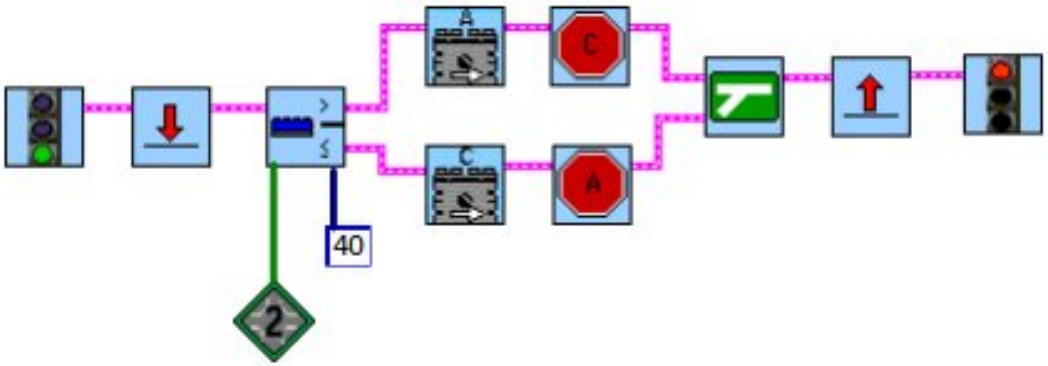
Joel Kammet
Brooklyn College
CUNY

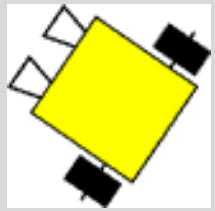
Conditional Branch: Light Sensor Fork

Not so useful:



Much better:





Joel Kammet
Brooklyn College
CUNY