Amorphous Medium Language

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LSMAS Workshop, July 2005

The Big Picture

Programming large spatially distributed systems is too hard!

- Reduce complexity by **programming continuous space** and **compiling for discrete agents**
- Increase reuse by **functional composition** of processes

A Farming Problem

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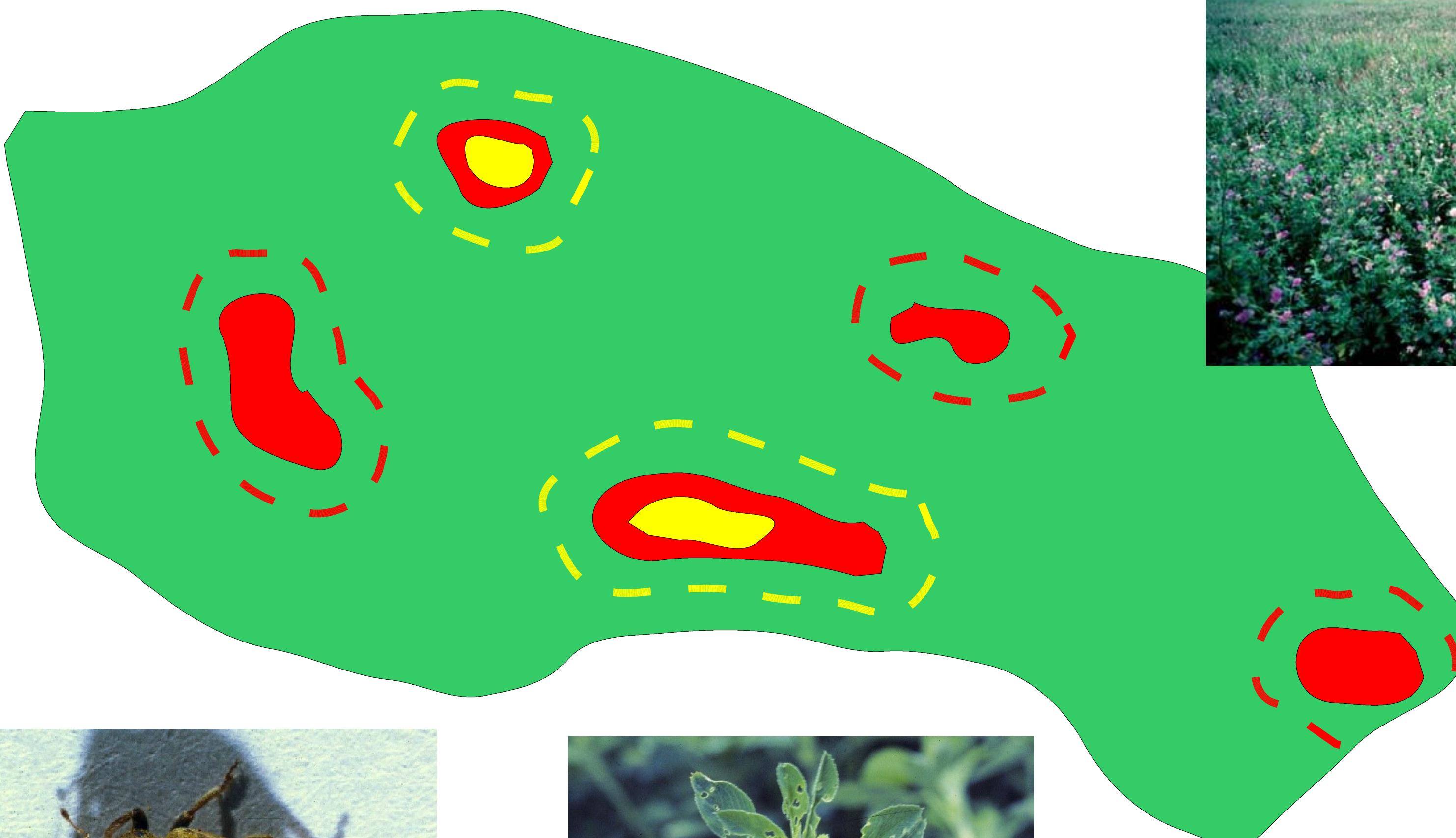

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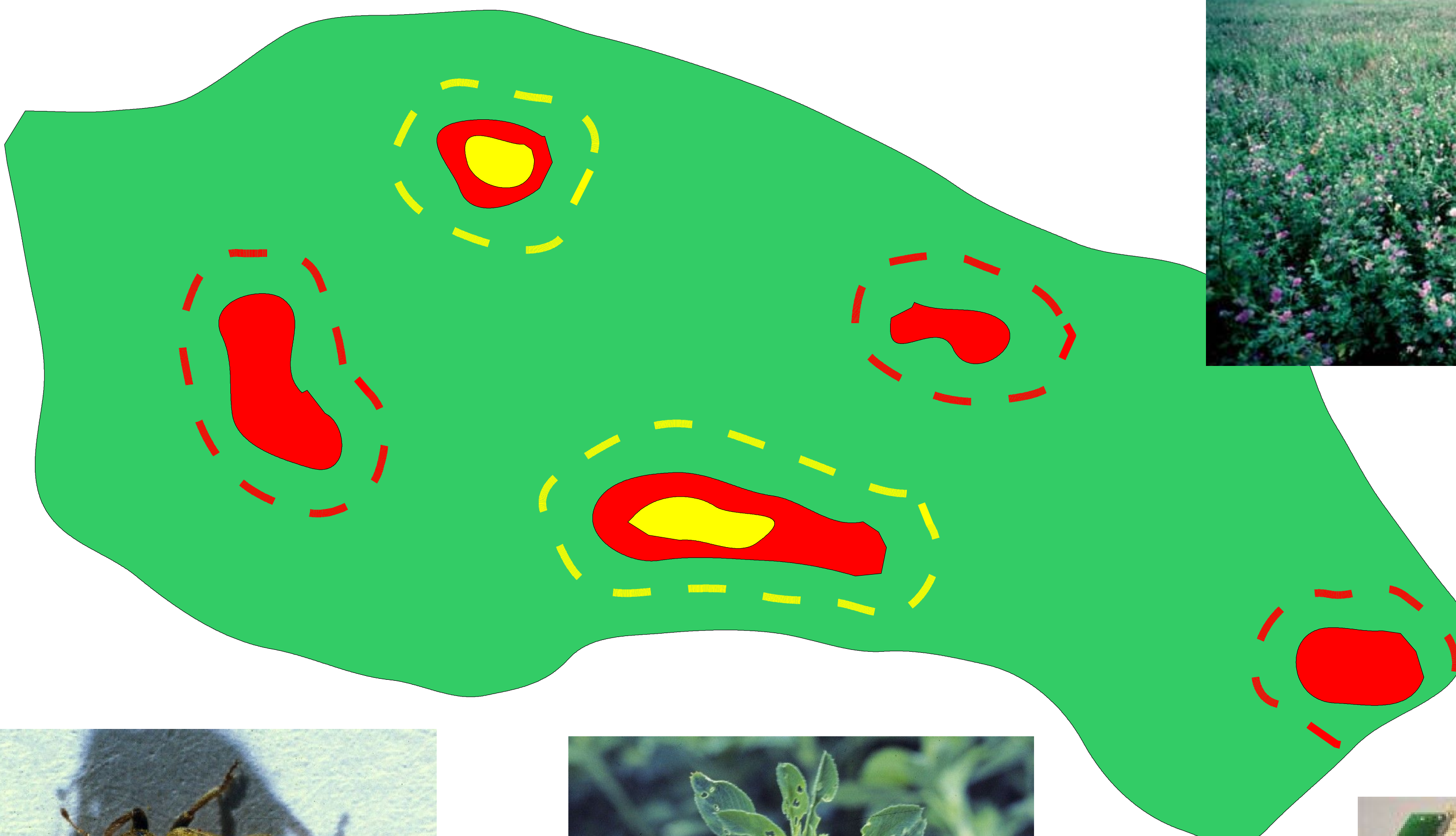
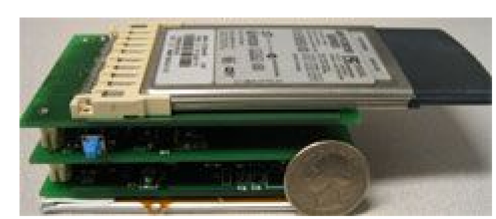
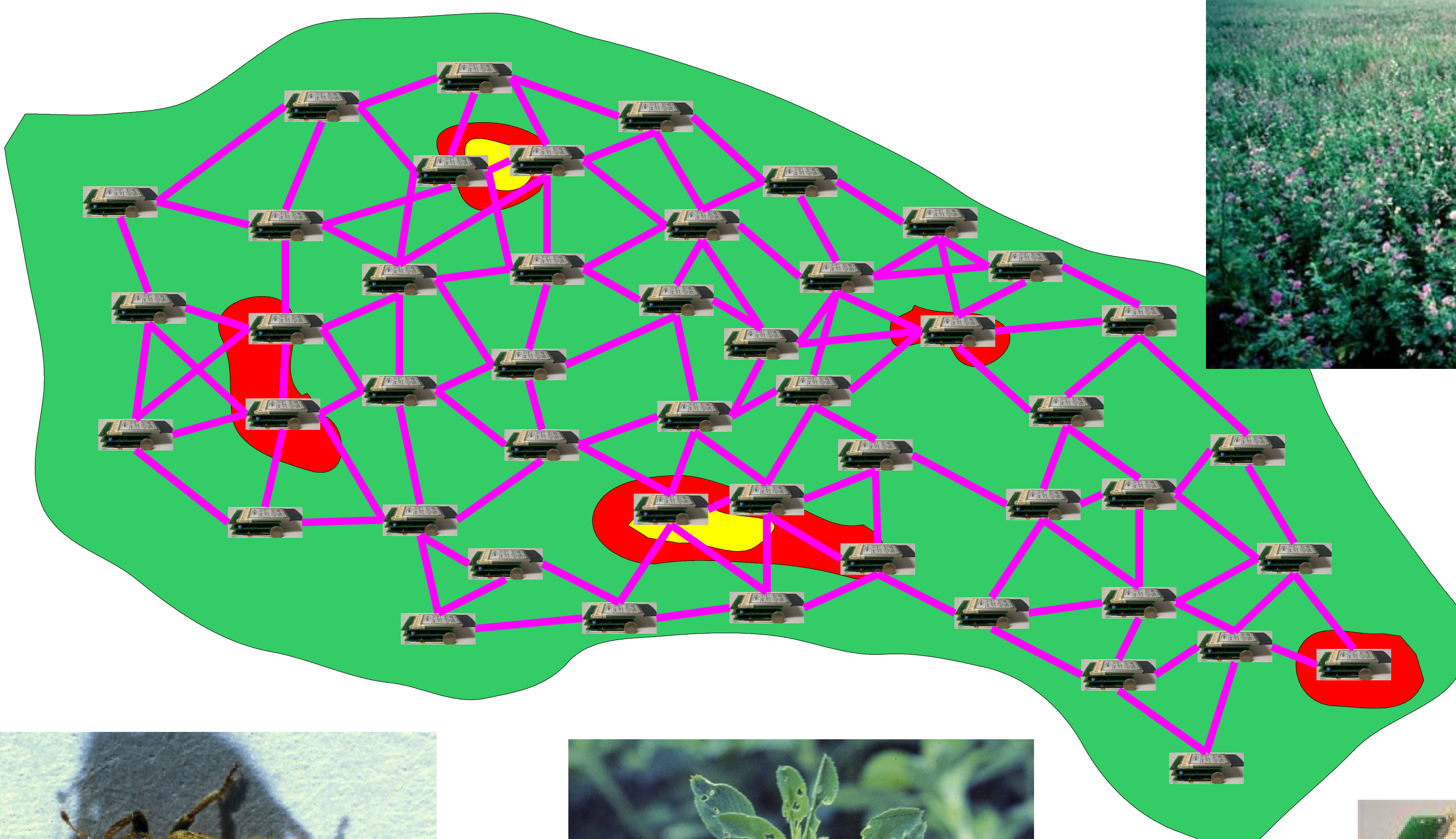




Solar powered UCI DuraNode

A Farming Problem



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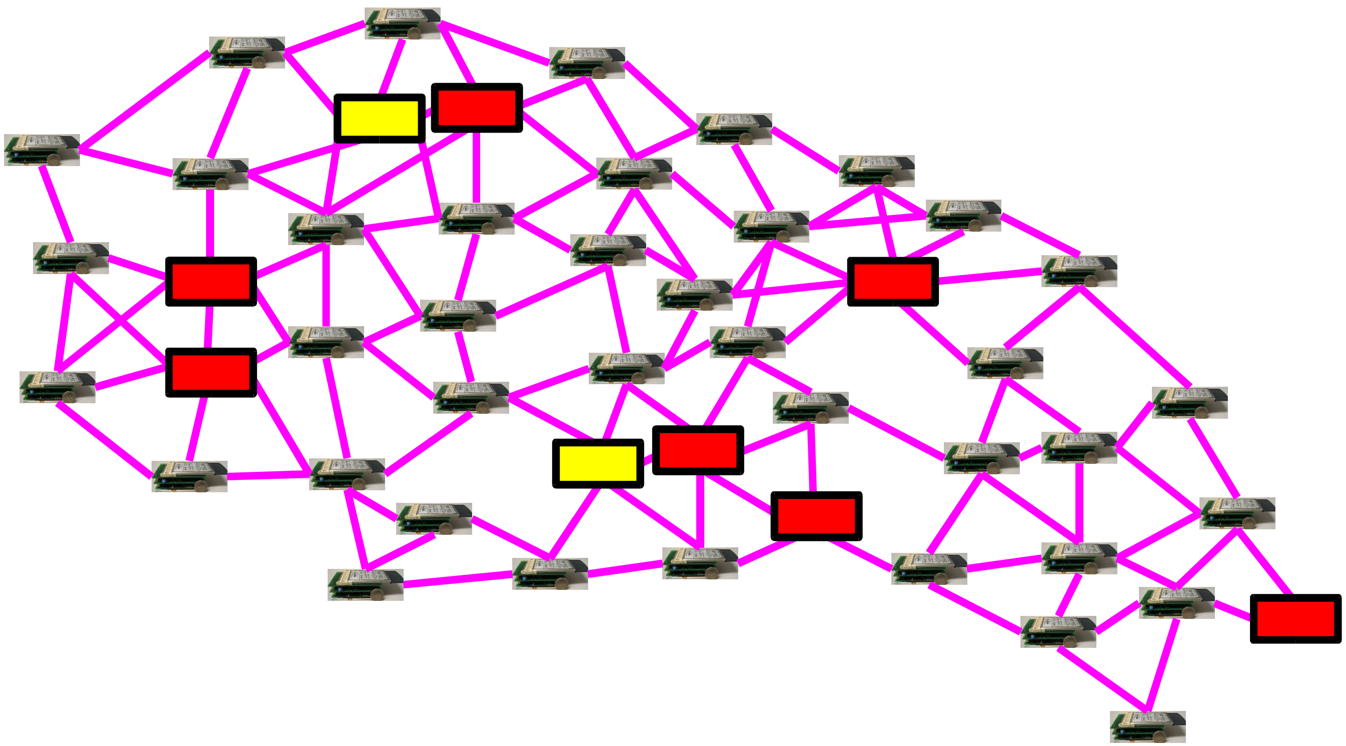
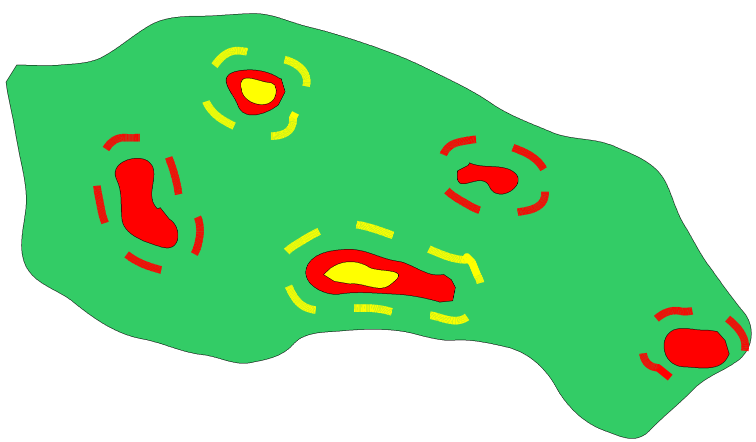
A Farming Problem

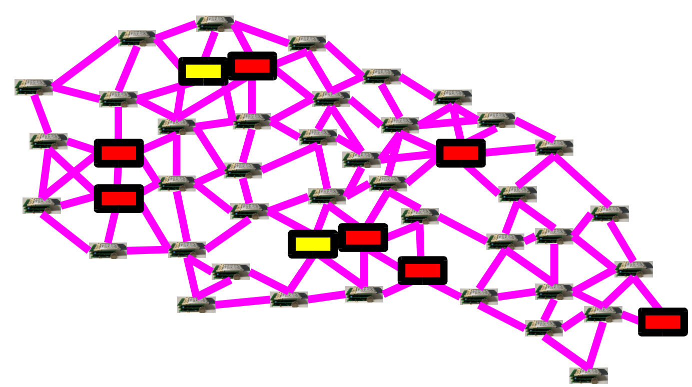


Wait a minute! Weren't we programming a farm?

We need an Abstraction Barrier!



What behavior we want from the **space**



How a **network** of **agents** reliably produce the behavior

Related Work

- Amorphous Computing
  - [Coore 99], [Nagpal 01], [Kondacs 03]
- Paintable Computing [Butera 02]
- GHT [Ratnasamy et al. 02], TinyDB [Madden et al. 02]
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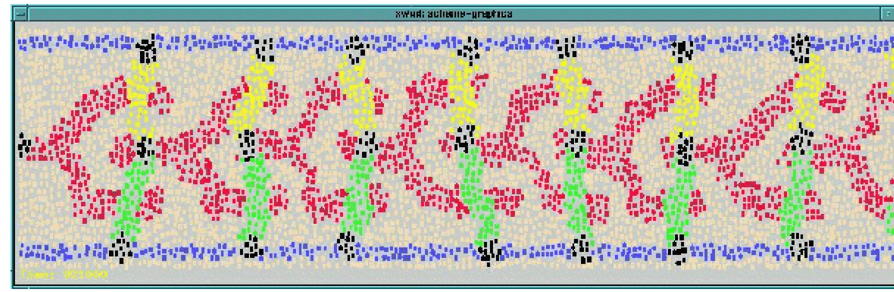

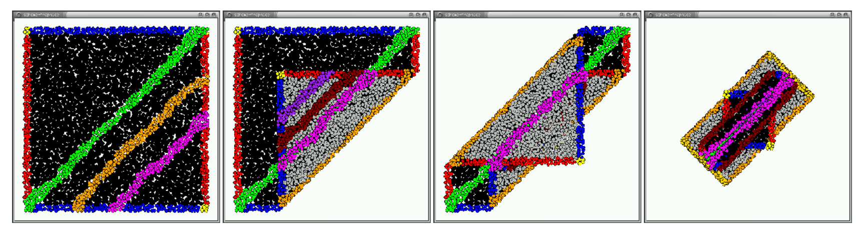

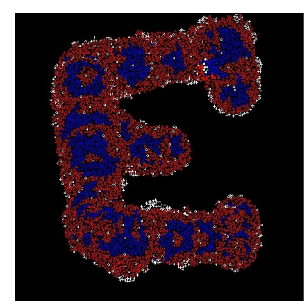

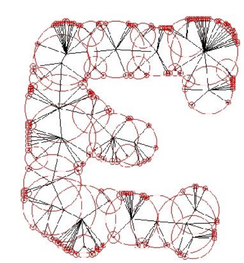

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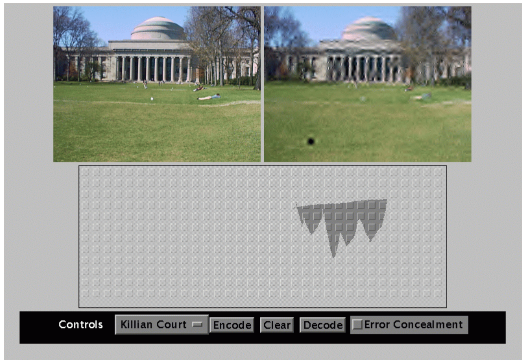

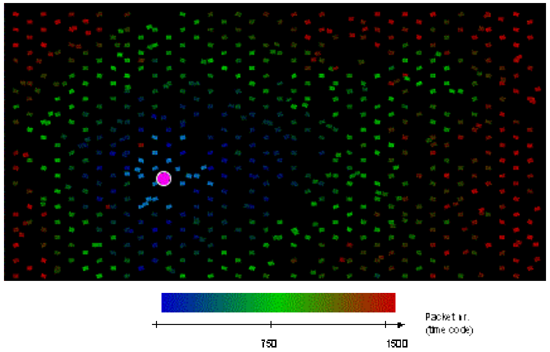

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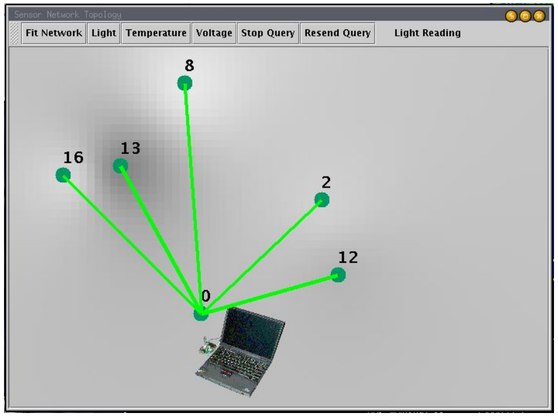

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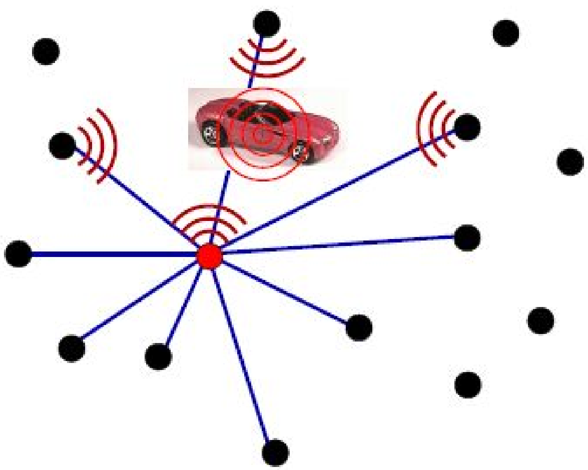
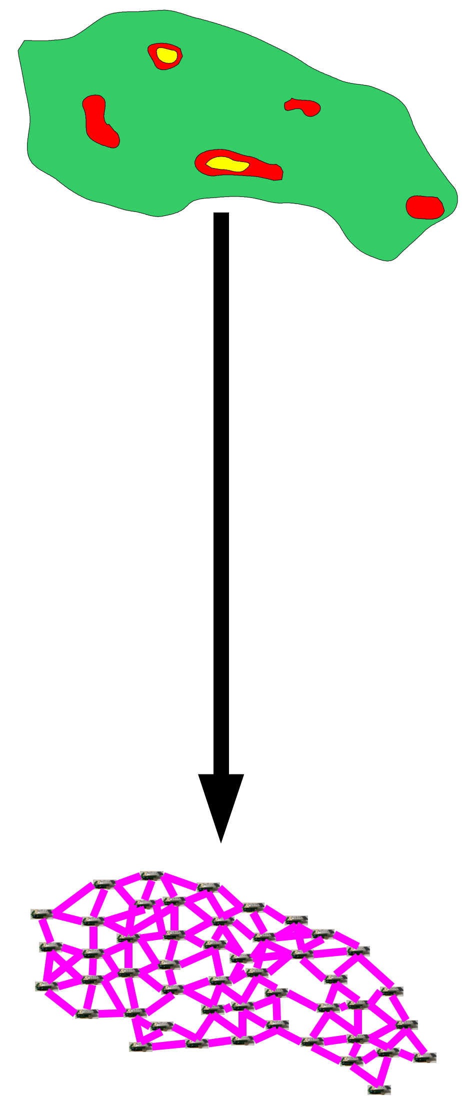


Amorphous Medium Language

- Global program→local action→global behavior
- Implicit distribution, coordination, communication
  - Program continuous space
  - Compile for discrete devices
  - Infrastructure supplied robust coordination primitives
- Functional composition of programs

```
(defun pest-management ()
  (in-components
   (dilate 2 (select-region (> (sense :bugs) 0.2)))
   (reduce-region #'max (sense :bugs) 0)))
```

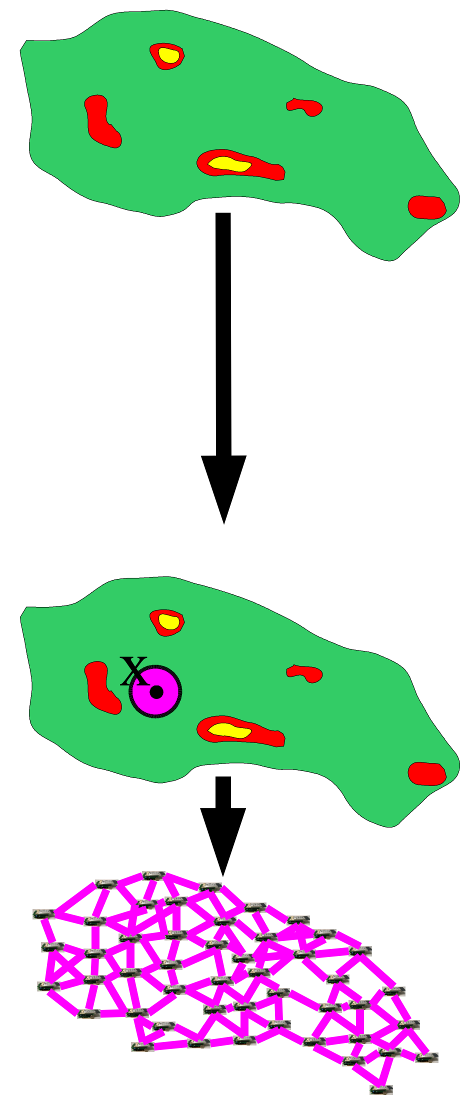
AML: Two Compatible Models



- Global Model (continuous regions)
  - reduce-region, in-components, select-region, dilate
- Discrete Model (agents, messages)
  - send, receive, sleep, sense, act

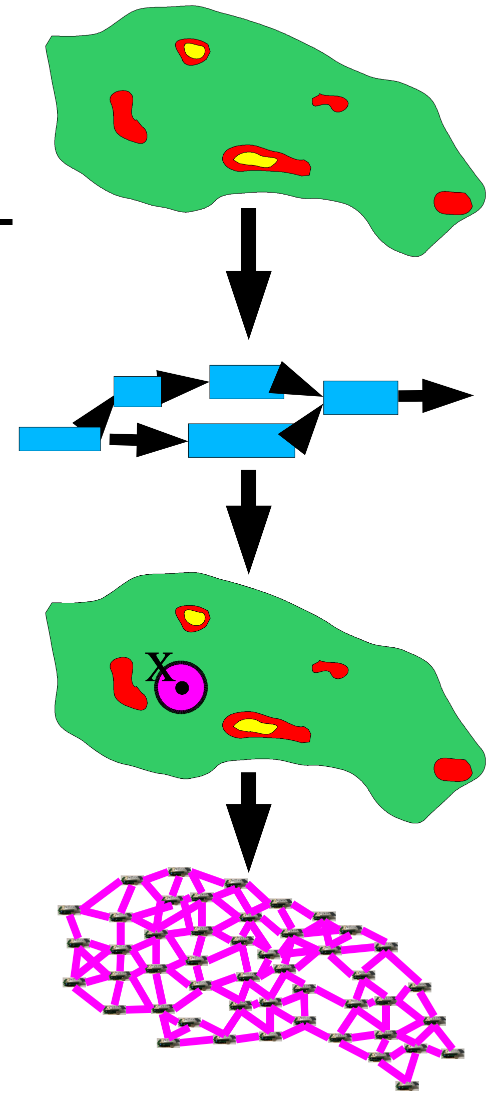
AML: ~~Two~~ 3 Compatible Models

- Global Model (continuous regions)
  - reduce-region, in-components, select-region, dilate
- Neighborhood Model (continuous neighborhoods)
  - exposed-state@, reduce-neighbors
- Discrete Model (agents, messages)
  - send, receive, sleep, sense, act

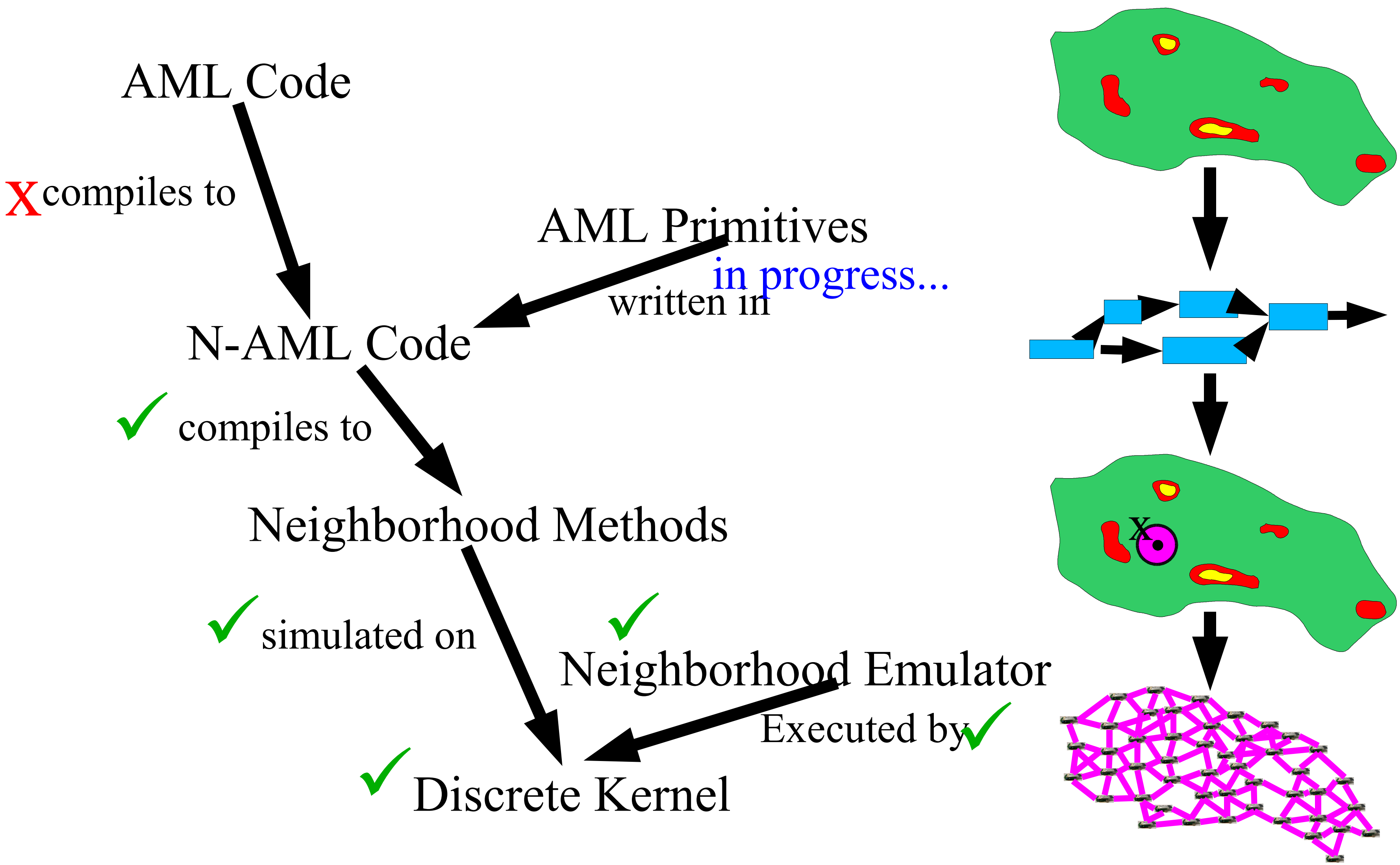


AML: ~~Two~~ ~~3~~ 4 Compatible Models

- Global Model (continuous regions)
  - reduce-region, in-components, select-region, dilate
- Neighborhood AML (composable nbrhood processes, infrastructure)
- Neighborhood Model (continuous neighborhoods)
  - exposed-state@, reduce-neighbors
- Discrete Model (agents, messages)
  - send, receive, sleep, sense, act



Programming in AML



Compiling AML to N-AML

AML:

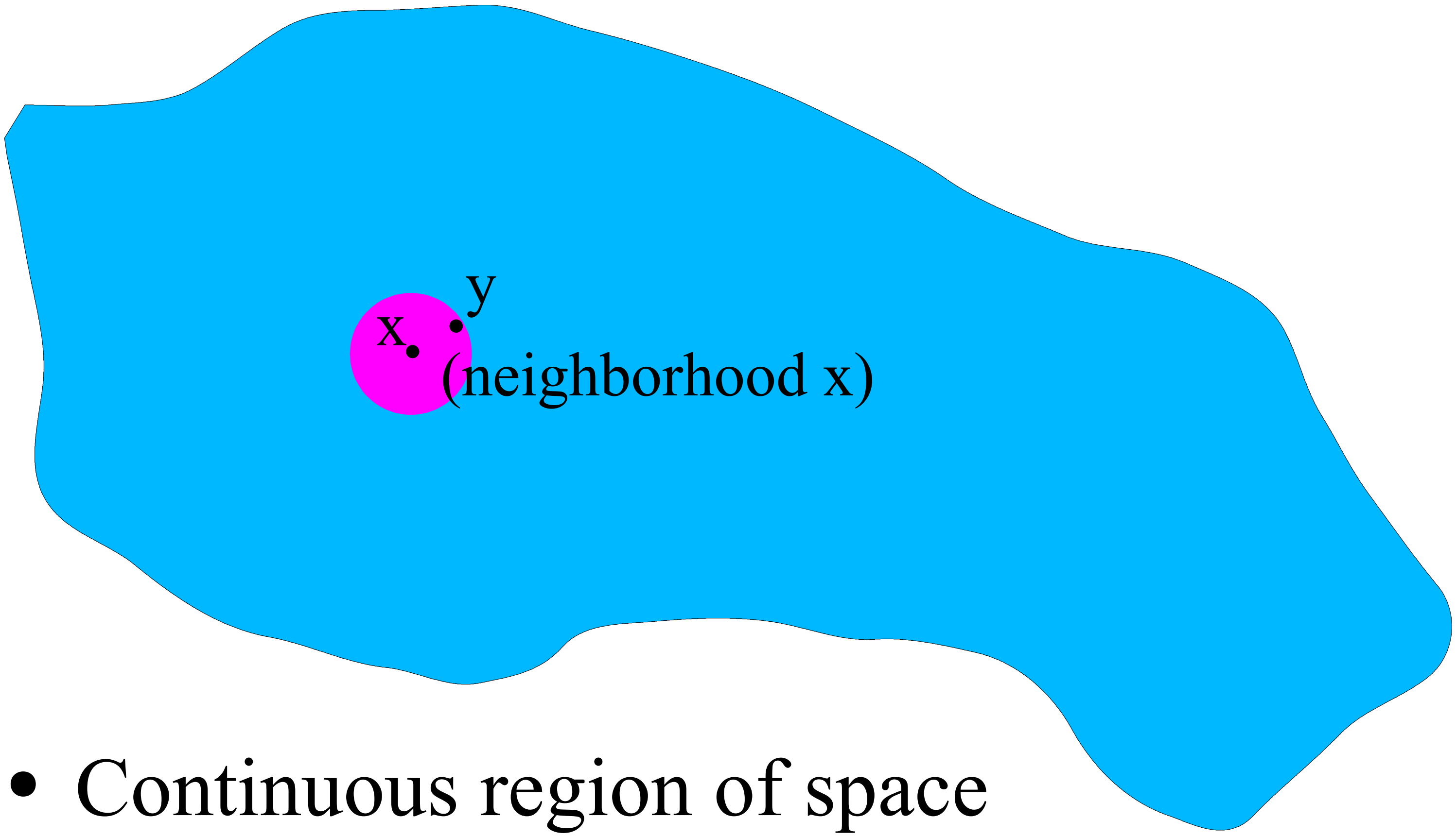
```
(defprocess pest-management ()
 (in-components
  (dilate 2 (select-region (> (sense :bugs) 0.2)))
  (reduce-region #'max (sense :bugs) 0)))
```

N-AML:

```
(defun pest-management ()
 (where
  (dilate 2 (lambda (place) (> (sense-bugs place) 0.2)))
  (gossiped-value #'max #'sense-bugs 0)))
```

- Compilation is straightforward, implementing reduce-region is difficult

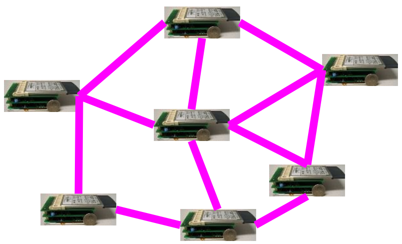
Neighborhood Model



- Continuous region of space
- Each point is a separate agent
- Agents share (delayed) exposed state w. neighbors

Discrete Model

- Dozens to billions of simple, unreliable agents
- Distributed through space, communicating by local broadcast



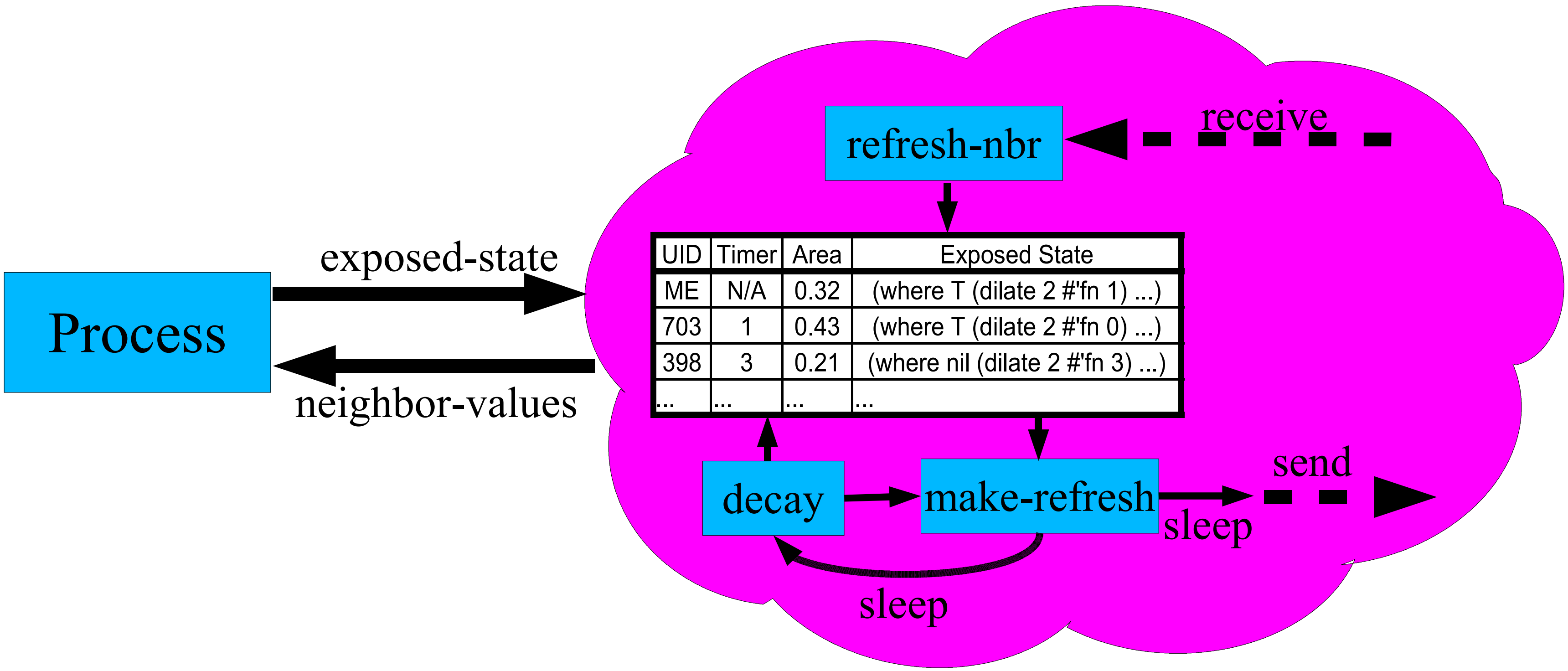
- Agents may be added or removed
- No global services (e.g. time, naming, routing, coordinates)
- Relatively cheap power, memory, processing
- Agents are immobile*

*or slow and dense enough to run Virtual Stationary Nodes [Dolev et al. 05]

Places

- Places are Points/Agents
- State at a place:
  - Unique ID
  - Sensors (e.g. bug-detector, temperature)
  - Actuators (e.g. pesticide sprayer, LEDs)
  - Running process

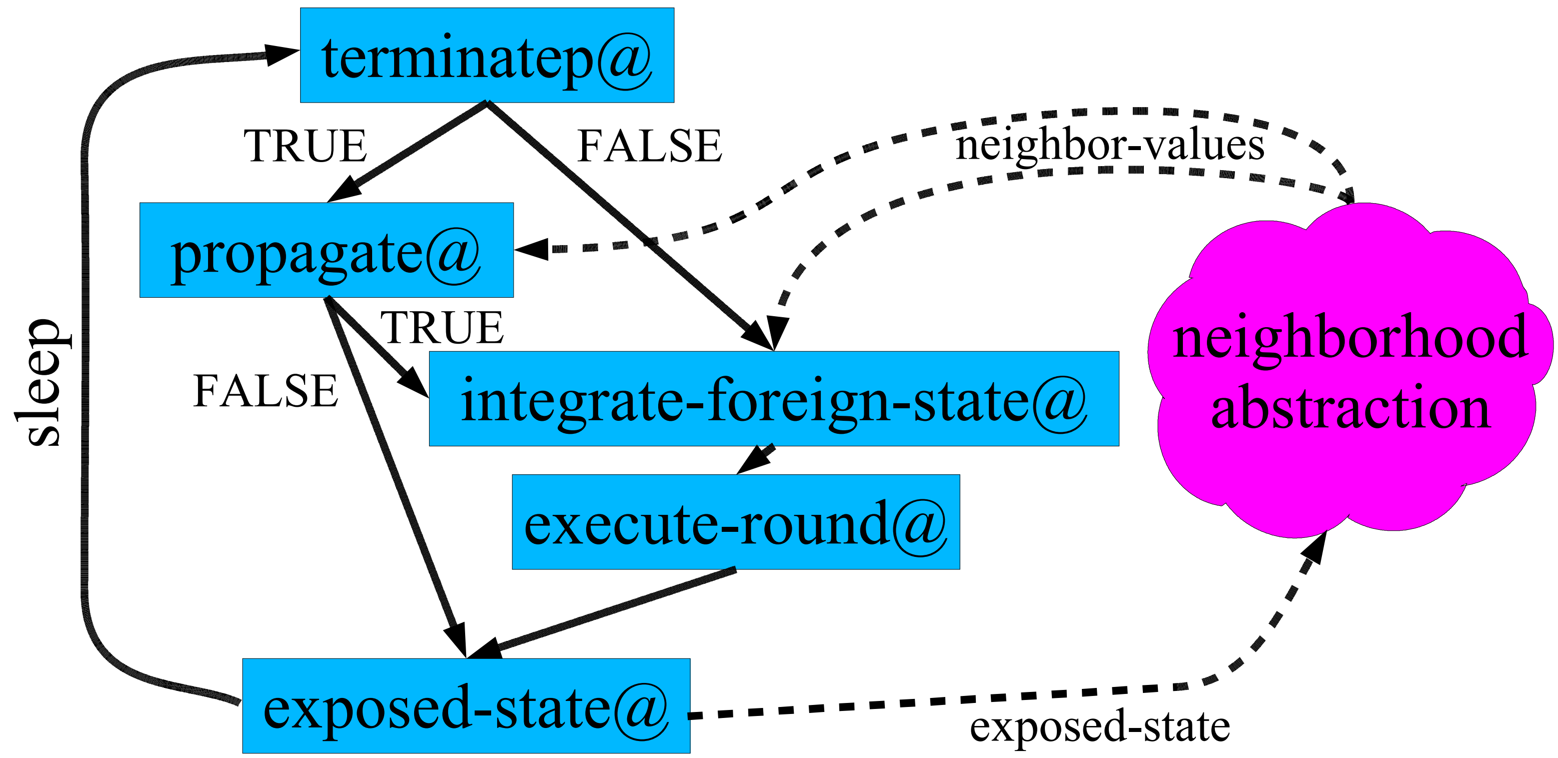
Neighborhood Abstraction



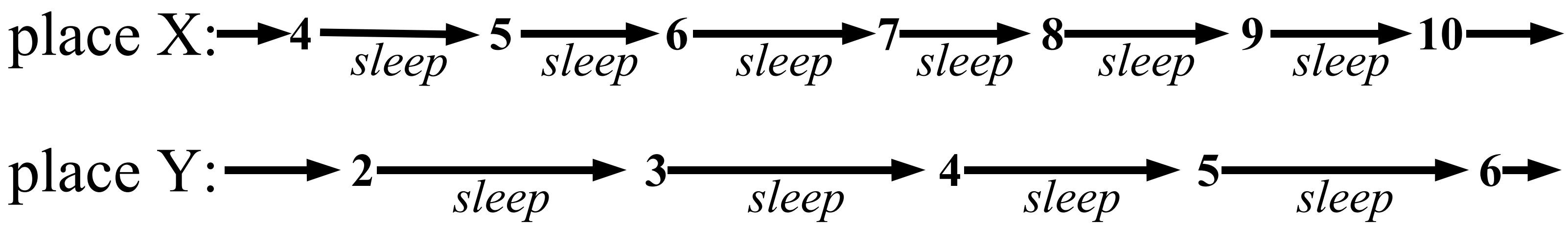
UID	Timer	Area	Exposed State
ME	N/A	0.32	(where T (dilate 2 #'fn 1) ...)
703	1	0.43	(where T (dilate 2 #'fn 0) ...)
398	3	0.21	(where nil (dilate 2 #'fn 3) ...)
...	...	...	...

- A process interacts with its neighborhood by:
  - setting the state exposed to its neighbors
  - sampling the state exposed by its neighbors

Process Execution Model

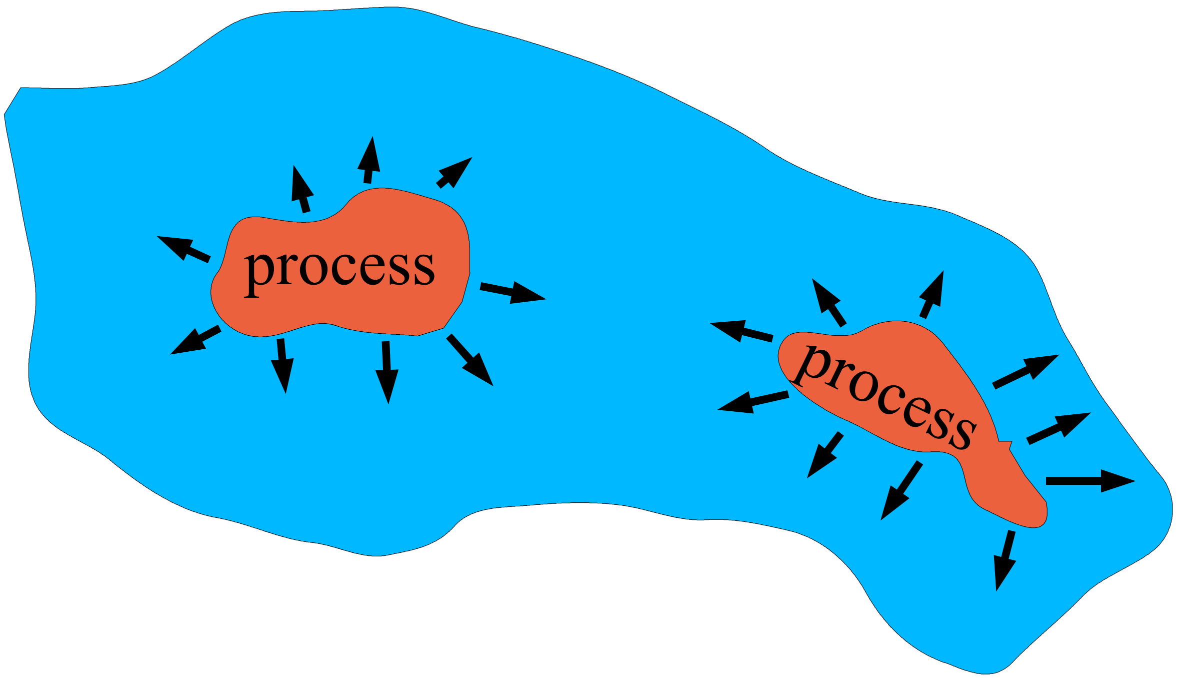


Handling Process Time



- Time is partially synchronous
  - Discrete rounds at each place
  - Different places have different clocks
- A process is an object containing state at round *T*
  - Round 0 specified as arguments, initial forms
  - Evolution specified as transition from *T* to *T+1*

Starting and Stopping Processes

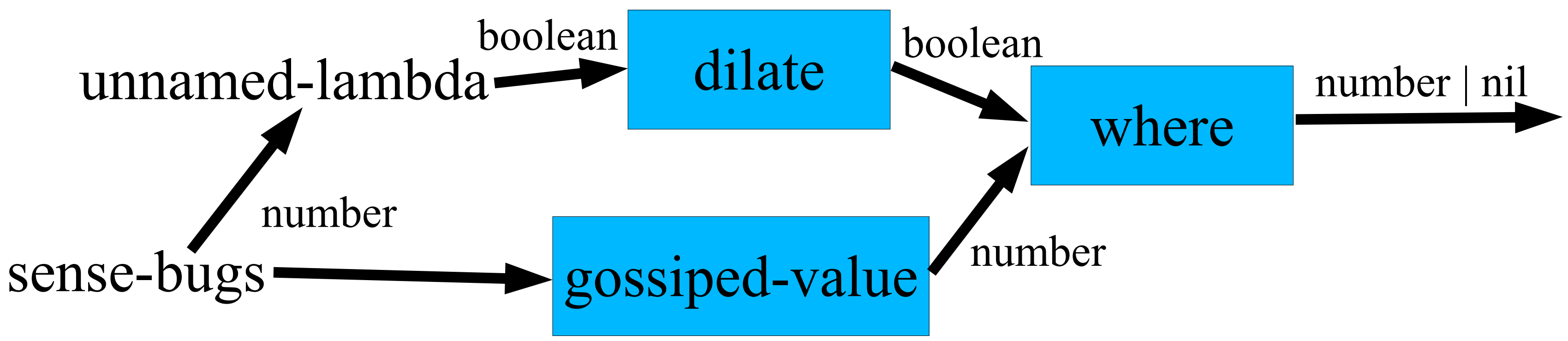


- Processes run when installed at a place
  - Places lacking a process attempt to install from neighbor's exposed state
- Processes are tested for termination each round

Handling Interaction with Neighbors

- Exposed state = constructor args, designated slots
  - Terminated processes expose nothing
- Incremental integration between rounds
  - special neighborhood forms
    - e.g. **(reduce-nbrs #'max v 0)**
    - may implicitly use hidden state
  - result returned during next transition between rounds

Handling Process Composition



- A process produces a time-series of values
  - A composed process is a tree of processes containing other processes in their state
    - Compose by filling process slots (implicit or explicit)
  - Execution protocol must distribute through the tree

Local functions as processes

(sense-bugs place) accesses a sensor

(exposed-state@ place #'sense-bugs)→'(function #'sense-bugs)

(propagate@ place 'function state)→#'sense-bugs

(integrate-foreign-state@ place #'sense-bugs state)→nil *[no effect]*

(execute-round@ place #'sense-bugs)→(sense-bugs place)

(terminatep@ place #'sense-bugs)→nil

- An ordinary function is a process that ignores its neighbors and never terminates.

Describing Processes

```
(defnonlocal where ((f nonlocal) (target nonlocal))
  (declare (termination (terminatep target)))
  (declare (exposing live))
  (declare (integration (target (and live target))))
  (with-state ((live nil))
    (setf live (evaluate f))
    (if live (evaluate target) nil)))
```

- *where* executes the *target* process only when the *f* process returns *true*

N-AML: Constructor & Class Def'n

```
(defnonlocal where ((f nonlocal) (target nonlocal))
  (declare (termination (terminatep target)))
  (declare (exposing live))
  (declare (integration (target (and live target))))
  (with-state ((live nil))
    (setf live (evaluate f))
    (if live (evaluate target) nil)))
```

```
(defclass where (nonlocal)
  ((f :accessor where-f :initarg :f)
   (target :accessor where-target :initarg :target)
   (live :accessor where-live :initarg :live)))
```

```
(defun where (f target)
  (let ((#:INST (make-instance 'where :f f :target target)))
    (with-slots (f target live) #:INST
      (setf live nil))
    #:INST))
```

N-AML: Execution & Termination

```
(defnonlocal where ((f nonlocal) (target nonlocal))
  (declare (termination (terminatep target)))
  (declare (exposing live))
  (declare (integration (target (and live target))))
  (with-state ((live nil))
   (setf live (evaluate f))
   (if live (evaluate target) nil)))
```

```
(defmethod terminatep@
   ((#:PLACE place) (#:INST where))
  (with-slots (f target live) #:INST
   (terminatep@ #:PLACE target)))
```

```
(defmethod execute-round@ ((#:PLACE place) (#:INST where))
  (with-slots (f target live) #:INST
    (progn
     (setf live (execute-round@ #:PLACE f))
     (if live
        (execute-round@ #:PLACE target)
       nil))))
```

N-AML: Communication

```
(defnonlocal where ((f nonlocal) (target nonlocal))
  (declare (termination (terminatep target)))
  (declare (exposing live))
  (declare (integration (target (and live target))))
  (with-state ((live nil))
    (setf live (evaluate f))
    (if live (evaluate target) nil)))
```

```
(defmethod integrate-foreign-state@
   ((#:PLACE place) (#:INST where) #:EXP)
 (when (type-match 'where #:EXP)
  (with-slots (f target live) #:INST
   (destructuring-bind (#:F #:TARGET #:LIVE) (cdr #:EXP)
     (integrate-foreign-state@ #:PLACE f #:F)
     (integrate-foreign-state@ #:PLACE target
                                    (and #:LIVE #:TARGET))))
  t))
```

```
(defmethod propagate@ ((#:PLACE place) (#:TYPE (eql 'where)) #:EXP)
 (when (type-match 'where #:EXP)
  (destructuring-bind (f target live) (cdr #:EXP)
   (setf f (propagate@ #:PLACE (when (consp f) (first f)) f))
   (setf target
     (propagate@ #:PLACE (when (consp (and live target))
                               (first (and live target)))
                  (and live target)))
   (unless (terminatep@ #:PLACE target)
     (make-instance 'where :f f :target target :live nil)))))
```

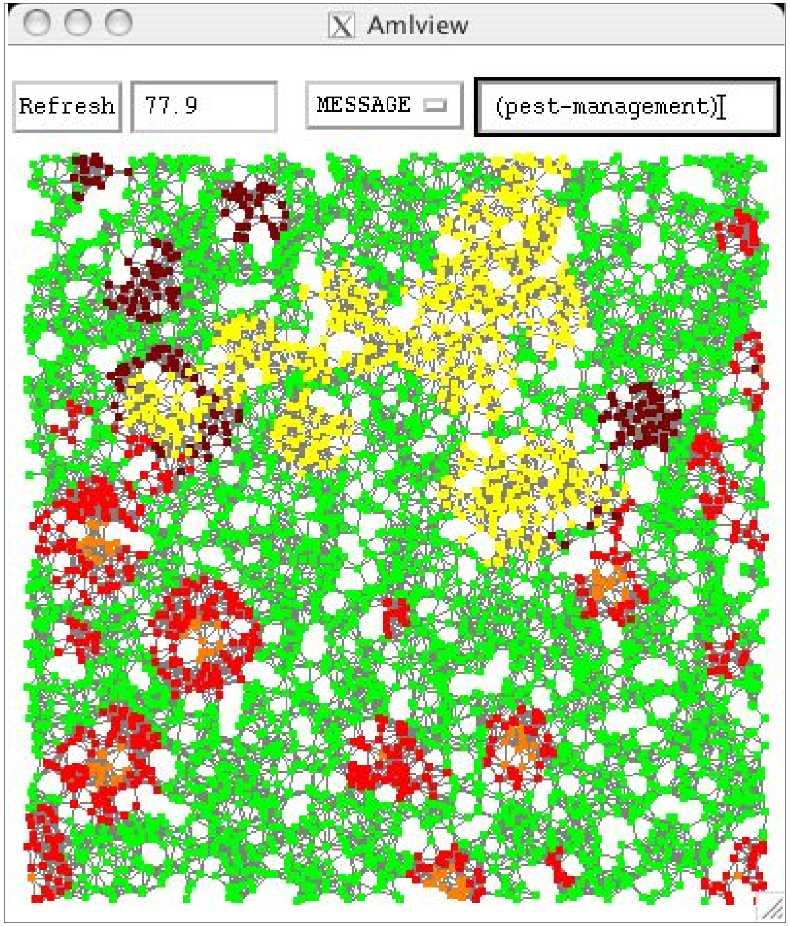
```
(defmethod exposed-state@ ((#:PLACE place) (#:INST where))
 (unless (terminatep@ #:PLACE #:INST)
  (with-slots (f target live) #:INST
   (list 'where (exposed-state@ #:PLACE f)
         (exposed-state@ #:PLACE target) live))))
```

Putting the pieces together...

```
(defun pest-management ()
  (where
   (dilate 2 (lambda (place) (> (sense-bugs place) 0.2)))
   (gossiped-value #'max #'sense-bugs 0)))
```

- Compound process created by functional composition of constructors

Simulated Execution



- Implemented in Allegro CommonLISP
- Runs 5000+ agent simulations

Future Work

- Optimization
- Discrete→Mica2 Motes
- Finish Global→Neighborhood
  - Update compiler
  - Improved **reduce-region** primitive

AML Contributions

- Abstraction barrier between **what** and **how** in large multi-agent systems
  - Computation models bridging from continuous regions of space to agents passing messages
  - Language supporting functional composition of processes
  - Primitives scalable to extremely large systems

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Thanks to Hal Abelson, Jonathan Bachrach, Gerry Sussman

Appendices

Isn't AML too expensive to use?

- Plentiful opportunities for optimization
- Communication is limited by congestion
  - *Maximum density* of bits, not number
- Power isn't as tight a constraint as often percieved
  - Powered networks: user-deployed (RoofNet), solar (DuraNode), embedded distribution (biological tissue)
  - Lots of research on energy storage
  - Tradeoff between control response and power usage

Using neighbor state

```
(defnonlocal dilate (n (source nonlocal))
  (declare (termination (terminatep source)))
  (declare (exposing r))
  (with-state ((r (1+ n)))
    (merge-nbrs (r) (setf r (min r (nbr r))))
    (when (evaluate source) (setf r -1))
    (incf r)
    (<= r n)))
```

- The *dilate* process returns *true* within *n* units of points where the *source* process returns *true*

Using neighbor state

```
(defnonlocal gossiped-value
                    (fuser (source nonlocal) &optional (base unspecified))
  (declare (exposing value))
  (declare (termination nil))
  (with-state ((value base))
    (setf value
      (funcall fuser (evaluate source) (reduce-nbrs fuser value base)))))
```

- The *gossiped-value* process uses *fuser* to reduce the values of the *source* process to the same summary value at every place