Programming Outdoor Distributed Embedded Systems

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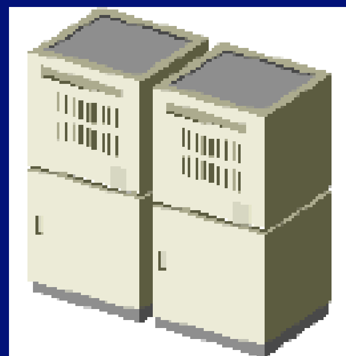
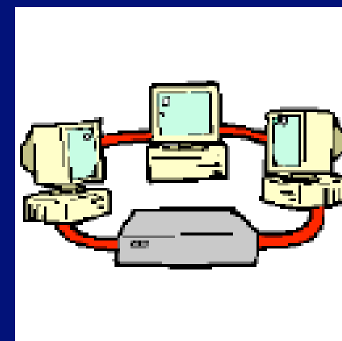
Indoor Distributed Computing

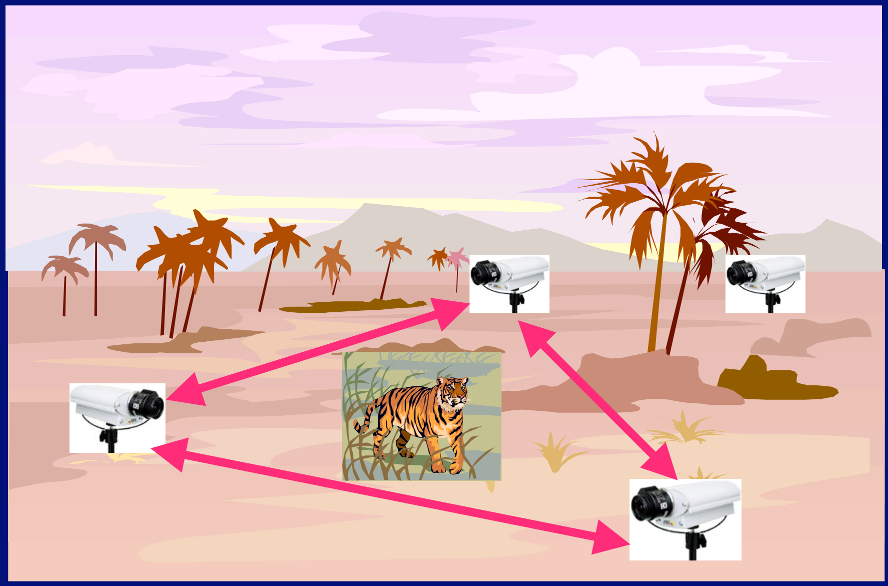




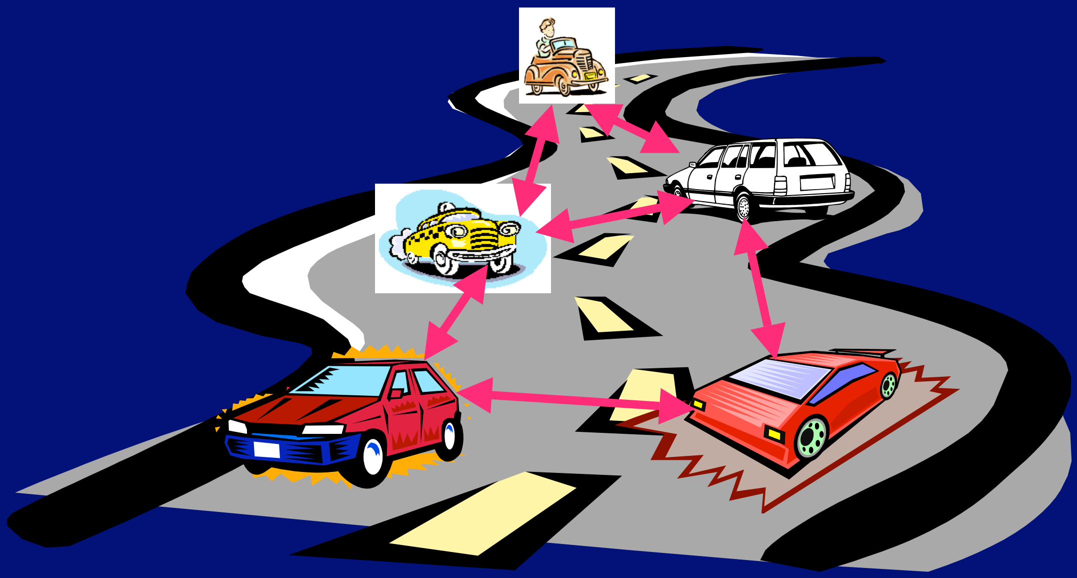
- Computing is distributed for performance or fault tolerance
- Nodes are computationally equivalent
- Configuration is stable (failures are exceptions)
- Networking is robust and has acceptable delays
- Relatively easy to program
  - Message passing or shared memory
  - Names are easy to translate to network addresses

Computers Go Outdoors

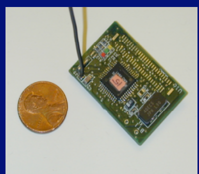
Distributed object tracking over a large geographical area



Cars collaborating for a safer and more fluid traffic



Outdoor Distributed Systems





- Embedded in non-traditional computing systems
- Functionally heterogeneous
- Distributed across the physical space
- Node's role in computation often driven by location
- Communicate through short-range wireless
- Create networks of embedded systems
  - Ad hoc topologies

How to Program Outdoor Distributed Embedded Systems?

- Recent research in networked embedded systems has focused on
  - Hardware
  - Operating Systems
  - Network Protocols
  - Data collection/dissemination in sensor networks
- Our research focuses on programmability
  - How to program distributed applications over networks of embedded systems?

Traditional Distributed Computing Does Not Work

- End-to-end data transfer may hardly complete
- Fixed address naming and routing (e.g., IP) are too rigid
- Difficult to deploy new applications in existing networks
- Outdoor distributed computing requires novel programming models and system architectures

Example

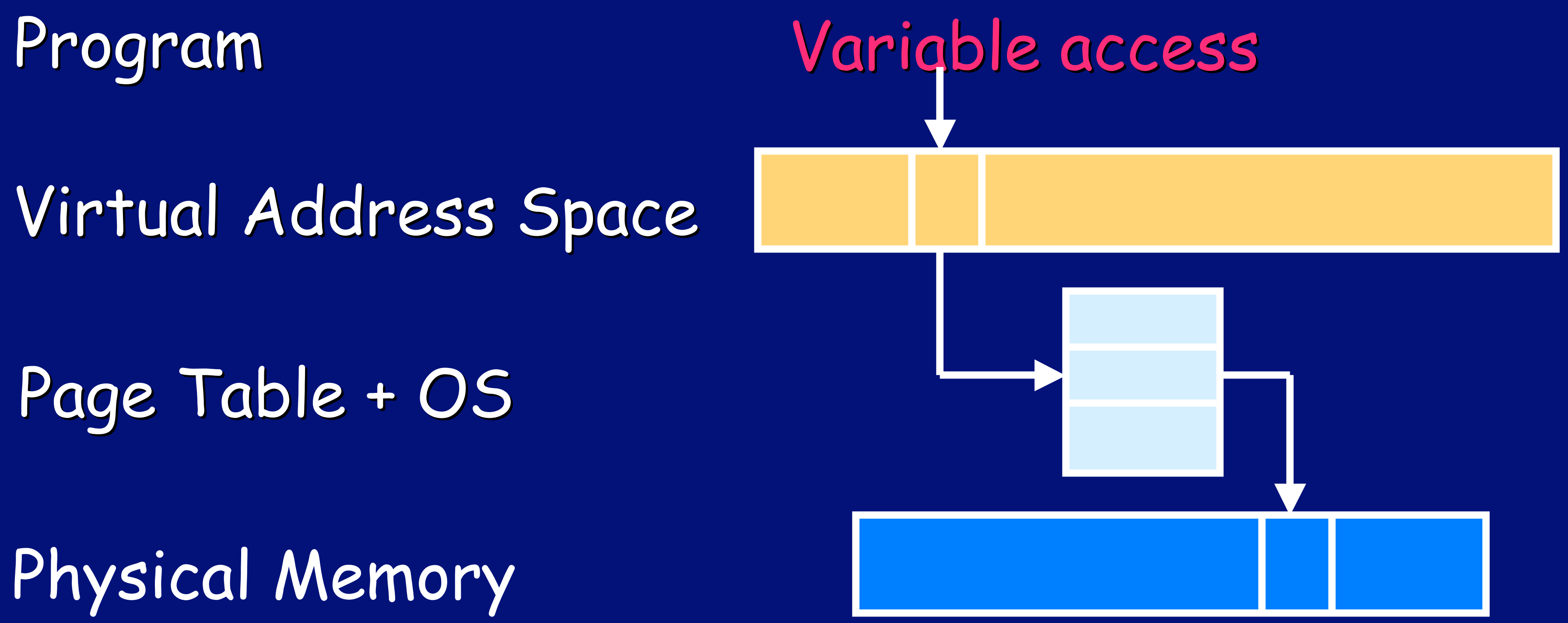
- Mobile sprinkler with temperature sensor
- Hot spot

- "Water the hottest spot on the Left Hill"
- Number and location of mobile sprinklers are unknown
- Configuration is not stable over time
  - Sprinklers move
  - Temperature changes

Outline

- Motivation
- Spatial Programming Model
- Smart Messages System Architecture
- Implementation and Evaluation
- Conclusions
- Future Work

Traditional Indoor Programming



- Programs access data through variables
- Variables mapped to physical memory locations
- Page Table + OS guarantees reference consistency

Outdoor Programming

- Application: Perform intrusion detection on Left Hill
- Need a simple programming model
  - Hide the networking details
  - Access to embedded systems as simple as access to variables

From Indoor to Outdoor Computing

Virtual Address Space	Space Region
Variables	Spatial References
Variables mapped to physical memory	Spatial references mapped to systems embedded in the physical space
Reference consistency	?
Bounded access time	?

Spatial Programming (SP) at a Glance

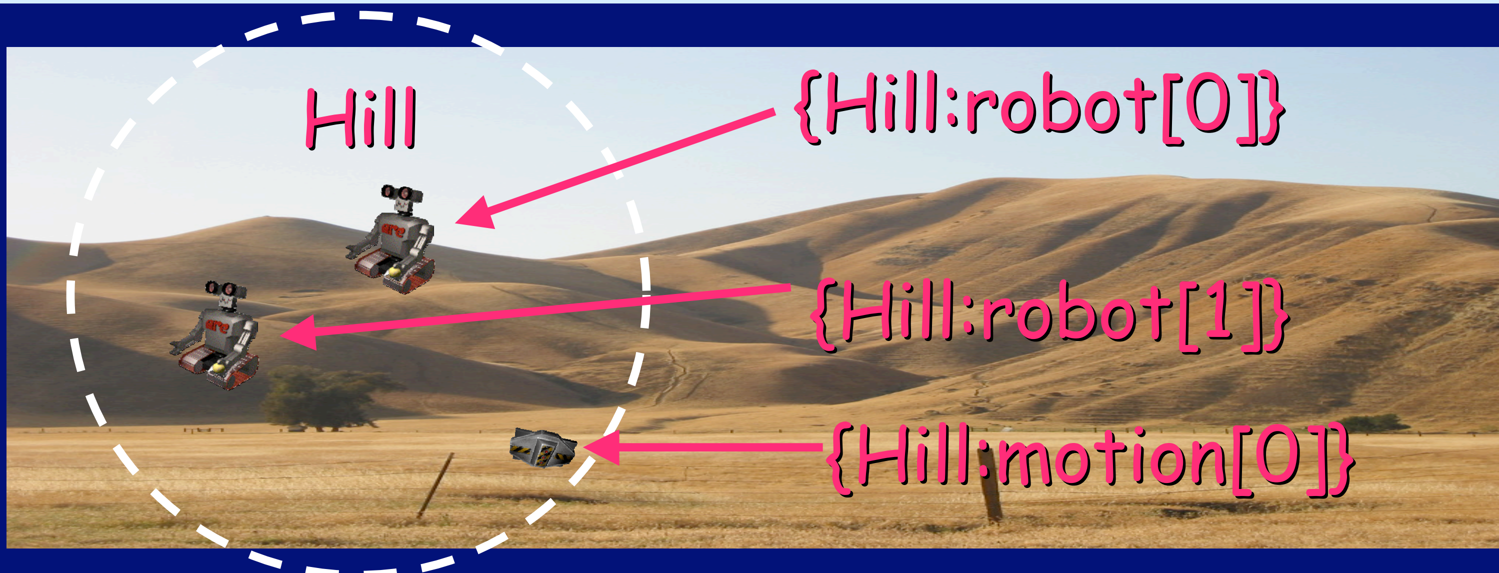
- Program outdoor distributed applications using spatial references
- Shields programmers from networking details by providing a virtual address space over networks of embedded systems
- Embedded systems/nodes named by their expected locations and properties

Space Regions

Hill = new Space({lat, long}, radius);

- Virtual representation of a physical space
- Similar to a virtual address space in a conventional computer system

Spatial References



- Defined as {space:property} pairs
- Virtual names for nodes in the network
- Similar to variables in conventional programming
  - Have meaning only within the application that defined them
- Indexes used to distinguish among similar systems in the same space region

Reference Consistency

- At first access, a spatial reference is mapped to an embedded system located in the specified space
- Mappings maintained in per-application Mapping Table (MT)

{space, property, index}→{network_address, location}

- Subsequent accesses to the same spatial reference must access the same system as long as it is located in the same space region (located using MT)

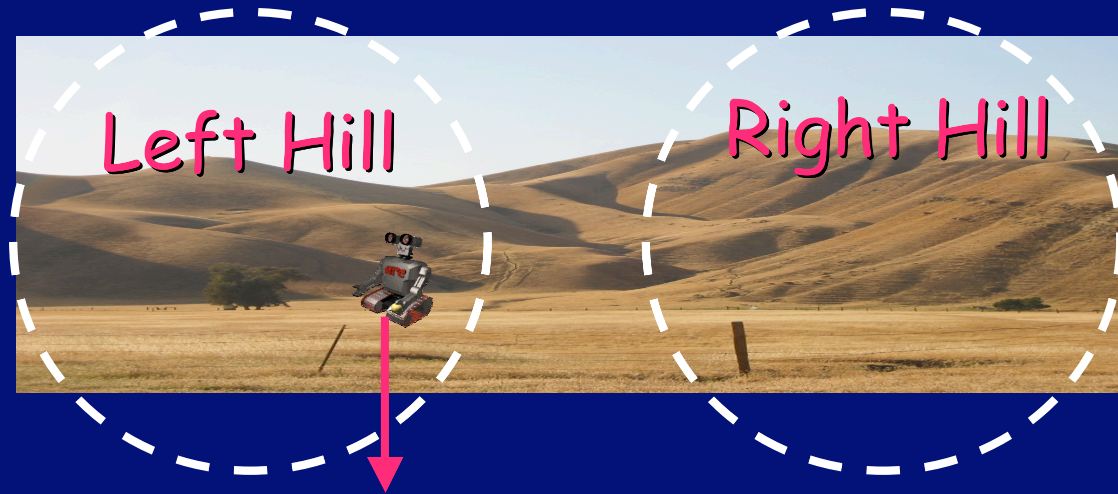
Reference Consistency Example

{Left_Hill:robot[0]}.move = ON;

Time

{Left_Hill:robot[0]}.move = OFF;

Space Casting



{Left_Hill:robot[0]}

Time

{Right_Hill:(Left_Hill:robot[0])}

Bounding the Access Time

- How to bound the time to access a spatial reference?
  - Discover an unmapped system for a new spatial reference
  - Mapped systems may move, go out of space, or disappear
- Solution: associate an explicit timeout with the spatial reference access

```
try{
  {Hill:robot[0], timeout}.camera = ON;
}catch(TimeoutException e){
  // the programmer decides the next action
}
```

Spatial Programming Example

- Mobile sprinkler with temperature sensor
- Hot spot

Application: Water the hottest spot on the Left Hill

```
for(i=0; i<1000; i++)
    try{
        if  ({Left_Hill:Hot[i], timeout}.temp > Max_temp)
                Max_temp = {Left_Hill:Hot[i], timeout}.temp;
                Max_id = i;
    }catch(TimeoutException e)
            break;
{Left_Hill:Hot[Max_id], timeout}.water = ON;
```

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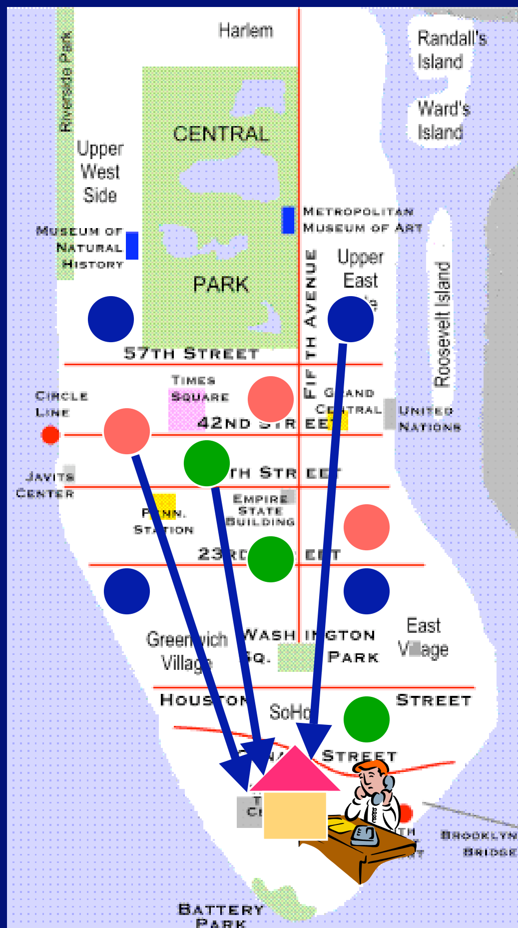
- Smart Messages System Architecture
- Implementation and Evaluation
- Conclusions
- Future Work

Smart Messages at a Glance

- Smart Message (SM)
  - User-defined distributed application
  - Composed of code bricks, data bricks, and execution control state
  - Executes on nodes of interest named by properties
  - Self-routes between nodes of interest
- Self-Routing
  - Application-level routing executed at every node
  - Applications can change routing during execution
- Cooperative Nodes
  - Execution environment (Virtual Machine)
  - Memory addressable by names (Tag Space)

"Dumb" vs. Smart Messages



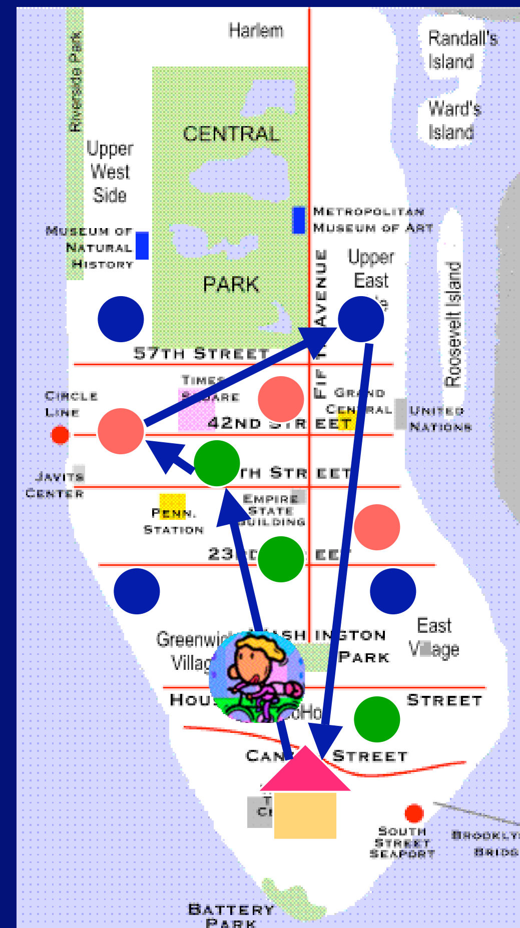
Data migration

Lunch:

Appetizer

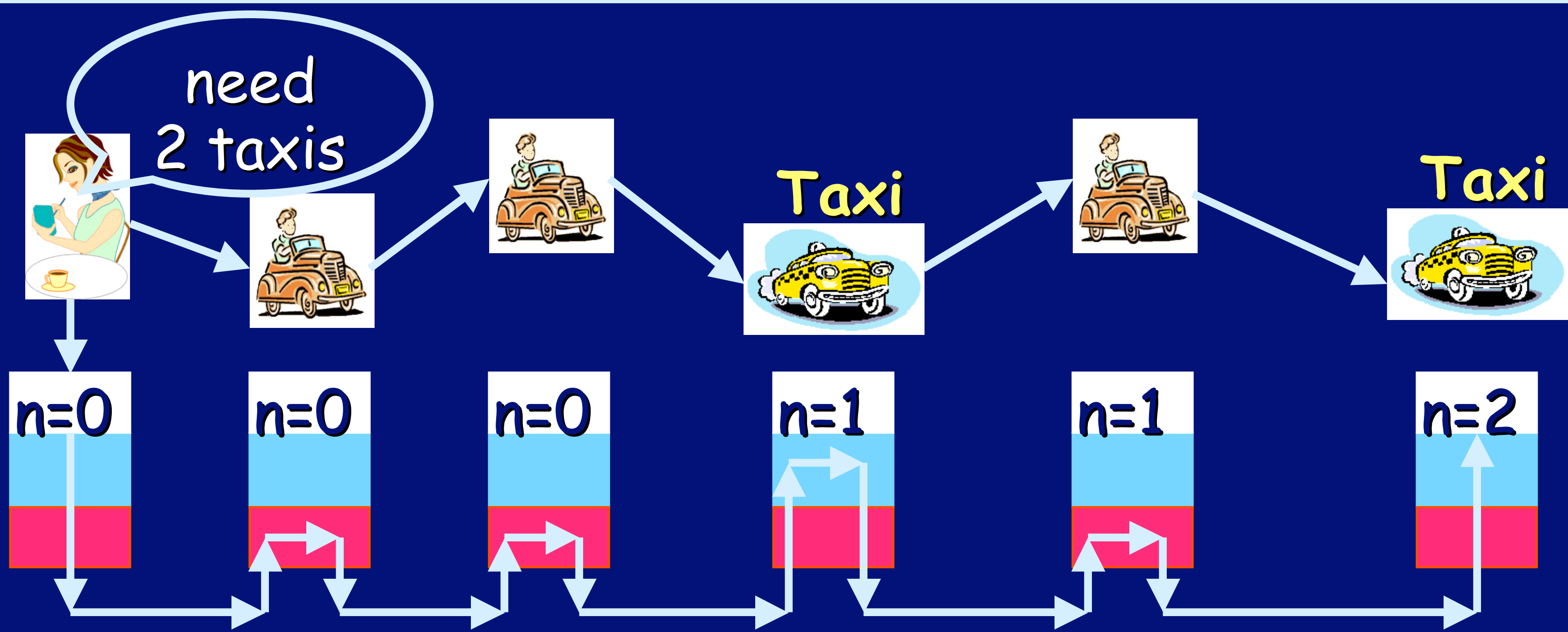
Entree

Dessert

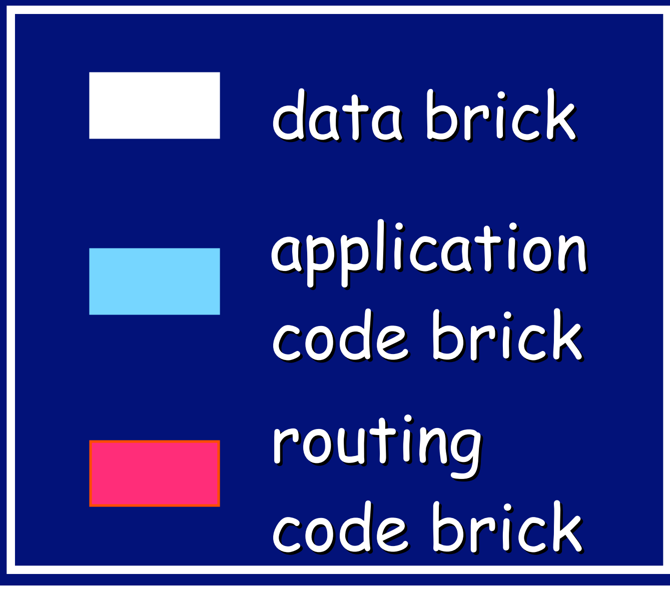


Execution migration

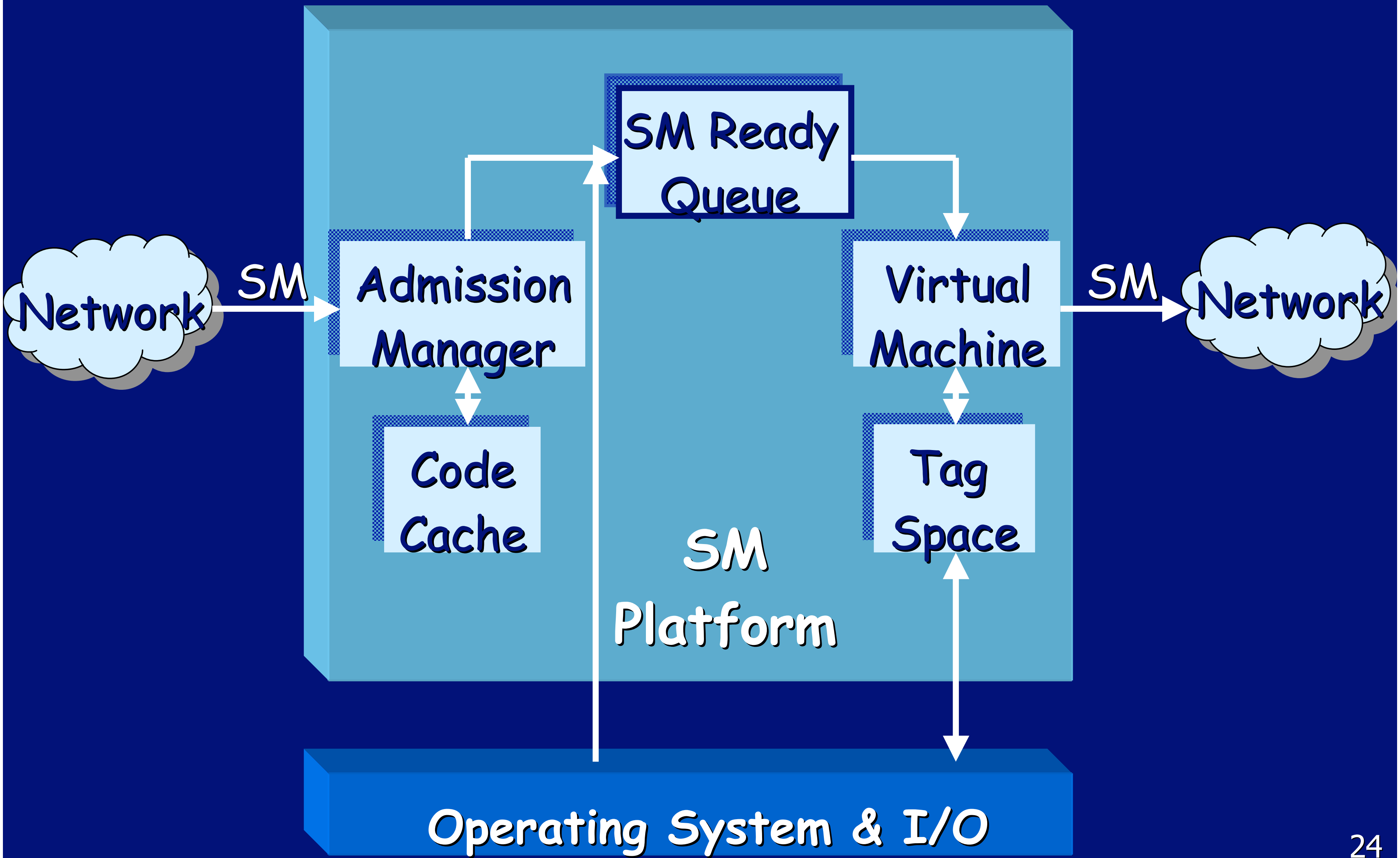
Application Example




```
n=0
while (n<NumTaxis)
    migrate(Taxi);
    if (readTag(Available))
        writeTag(Available, false);
        writeTag(Location, myLocation);
        n++;
```



Cooperative Node Architecture



Admission

- Ensures progress for all SMs in the network
- Prevents SMs from migrating to nodes where they cannot achieve anything
- SMs specify lower bounds for resource requirements (e.g., memory, bandwidth)
- SMs accepted if the node can satisfy these requirements
  - SMs transfer only the missing code bricks
- More resources can be granted according to admission policy

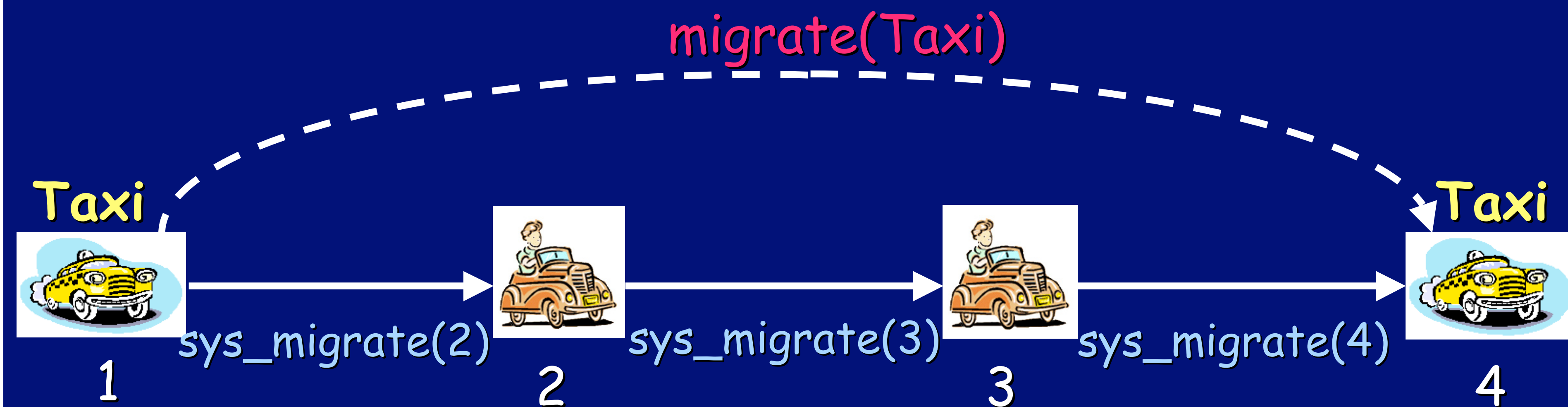
Execution at a Node

- Non-preemptive, but time bounded
- Ends with a migration, or terminates
- During execution, SMs can
  - Spawn new SMs
  - Create new SMs out of their code and data bricks
  - Access the tag space
  - Block on a tag to be updated

Tag Space

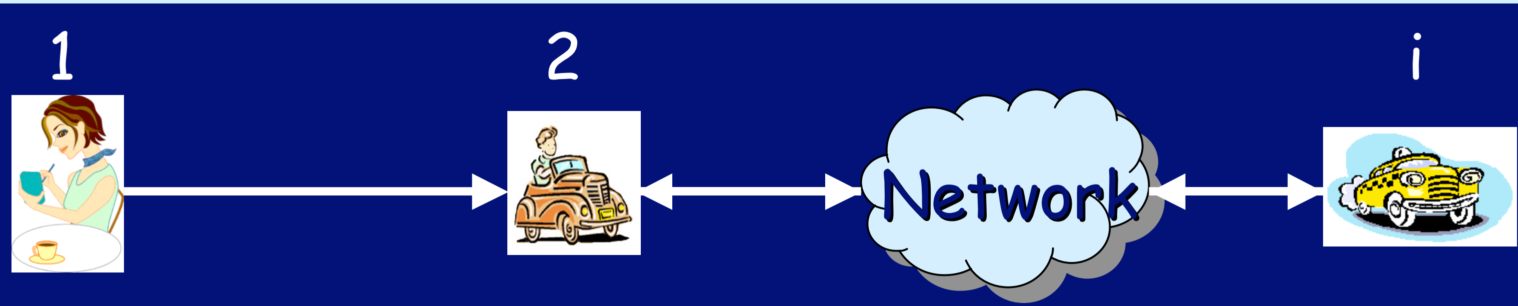
- Application tags: "persistent" memory for a limited duration across SM executions
- I/O tags: uniform interface for interaction with operating system and I/O subsystem
- Tags are used for
  - Content-based naming migrate(tag, timeout)
  - Inter-SM communication write(tag, data), read(tag)
  - Synchronization block(tag, timeout)
  - I/O access read(temperature)
- 5 protection domains for access control

Migration



- migrate()
  - implements routing algorithm
  - migrates application to next node of interest
  - names nodes in terms of arbitrary conditions on tag names and tag values
- sys_migrate()
  - one hop migration

Routing Example



RouteToTaxi = 2

RouteToTaxi = j

Taxi

```
migrate(Taxi){
  while(!readTag(Taxi))
    if (readTag(RouteToTaxi))
      sys_migrate(readTag(RouteToTaxi));
    else
      create_SM(DiscoverySM, Taxi);
      createTag(RouteToTaxi, lifetime, null);
      block_SM(RouteToTaxi, timeout);
}
```

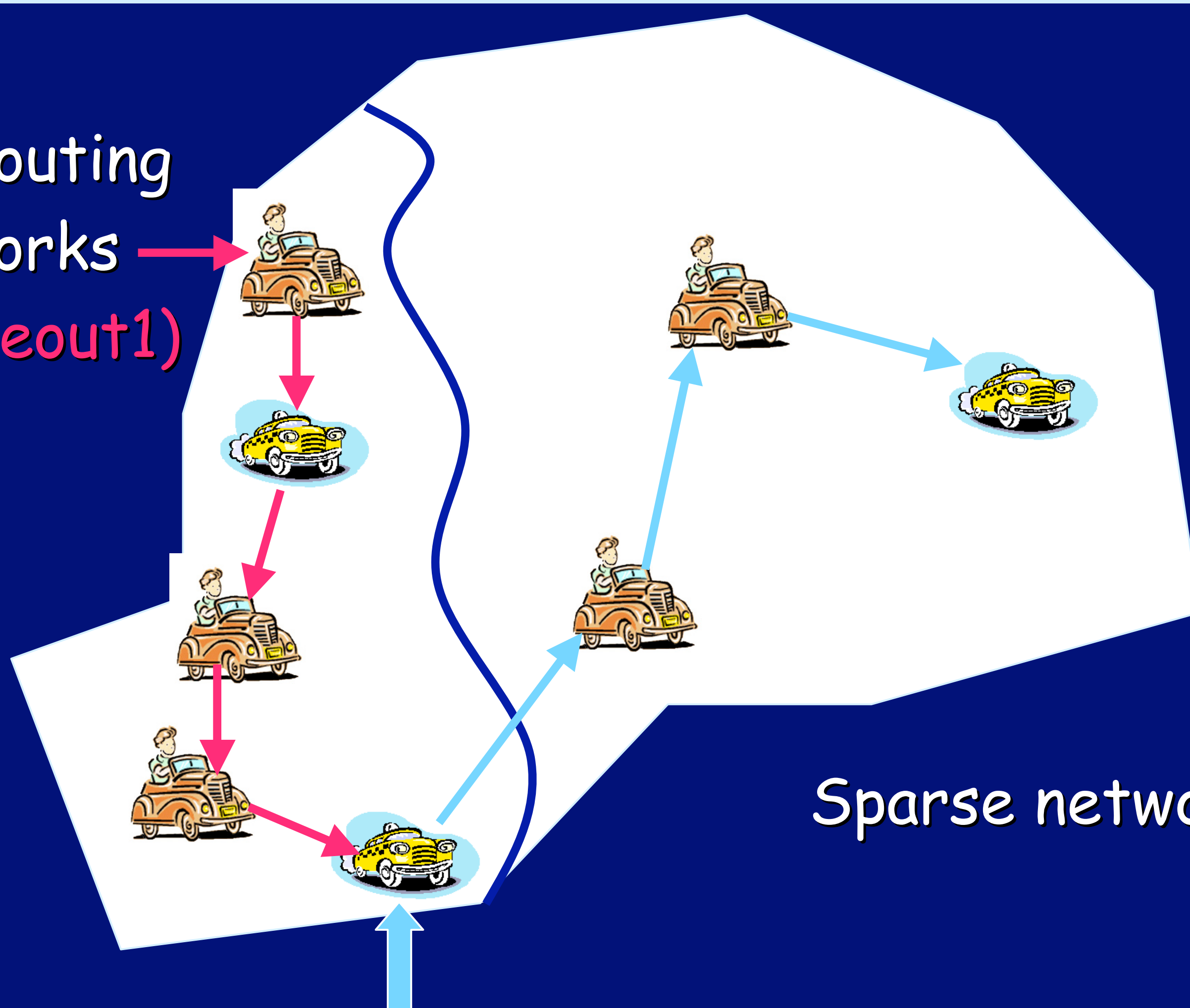
Self-Routing

- SMs carry the routing and execute it at each node
- SMs control their routing
  - Select routing algorithm (migrate primitive)
    - Multiple library implementations
    - Implement a new one
  - Change routing algorithm during execution in response to
    - Adverse network conditions
    - Application's requirements

Example of Dynamic Change of Routing

SM starts with routing for dense networks

migrate(Taxi, timeout1)



Dense network

Sparse network

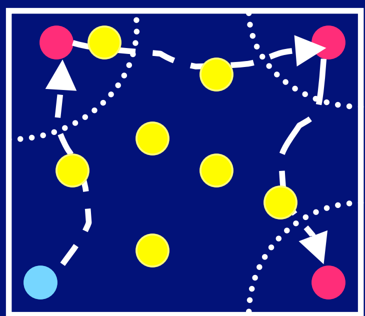
migrate timeouts

SM continues with routing for sparse networks

migrate(Taxi, timeout2)

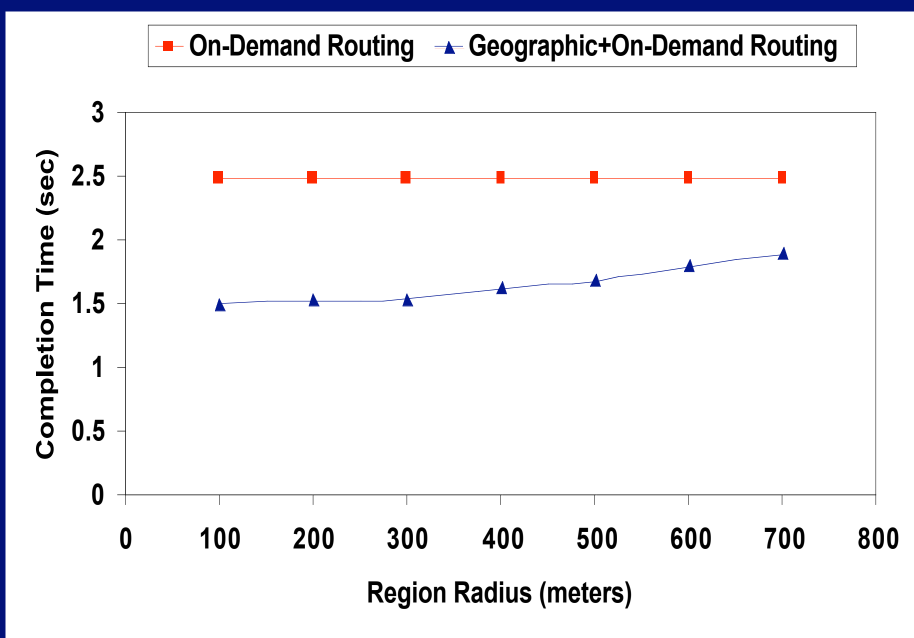
Self-Routing Simulation Results

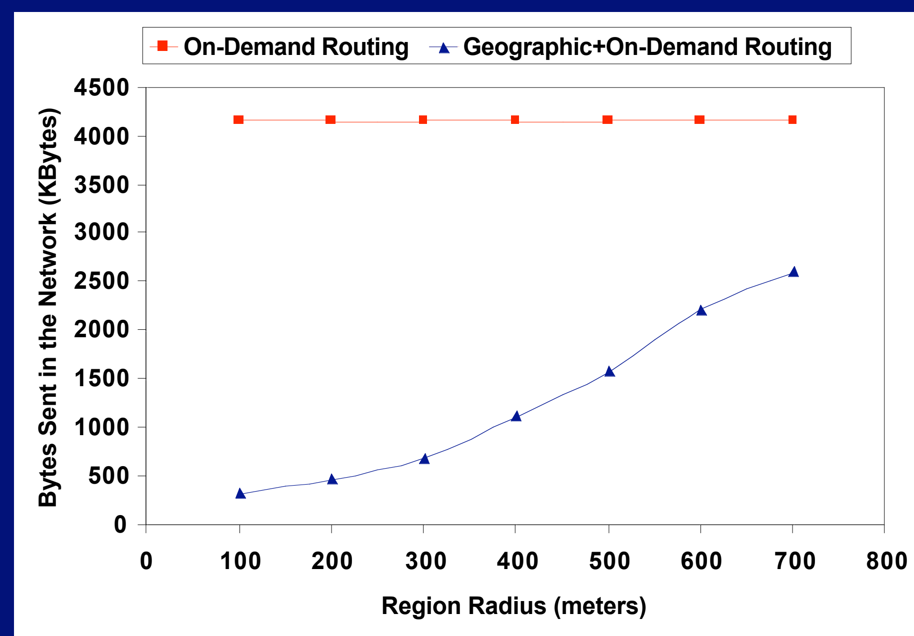
On-Demand Routing versus Geographic + On-Demand Routing



- 3 nodes of interest located in the corners have to be visited in clockwise order
- vary the radius from 100m to 700m

starting node   node of interest   other node





Prototype Implementation

- Modified version of Sun's Java K Virtual Machine
  - Small memory footprint (160KB)
- SM and tag space primitives implemented inside virtual machine as native methods (efficiency)
- Implemented I/O tags: GPS location, neighbor discovery, image capture, light [illegible] status

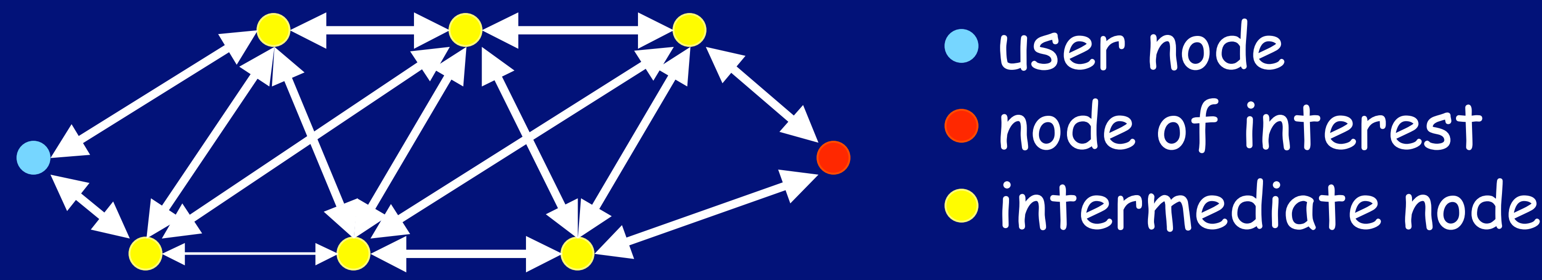
Prototype Node with GPS receiver and video camera

Lightweight Migration

- Traditional process migration difficult
  - Strong coupling between execution entity and host
  - Needs to take care of operating system state (e.g., open sockets, file descriptors)
- Tag space decouples the SM execution state from the operating system state
- SM migration transfers only
  - Data bricks explicitly specified by programmer
  - Minimal execution control state required to resume the SM at the next instruction (e.g., instruction

Experimental Results for Simple Routing Algorithms

HP iPAQs running Linux and using IEEE 802.11 for wireless communication



Routing algorithm	Code not cached (ms)	Code cached (ms)
Geographic	415.6	126.6
On-demand	506.6	314.7

Completion Time

Spatial Programming Implementation Using Smart Messages

- SP application translates into an SM
- Spatial reference access translates into an SM migration to the mapped node
- Embedded system properties: Tags
- SM self-routing (content-based and geographical routing)
- Reference consistency
  - Unique tag created when a spatial reference is mapped to a node
  - Name of the unique tag and the location of the node stored in Mapping Table (MT)

SP Library Using SMs: Example

Spatial Reference Access

Max_temp = {Left_Hill:Hot[1], timeout}.temp;

Smart Message

Mapping Table

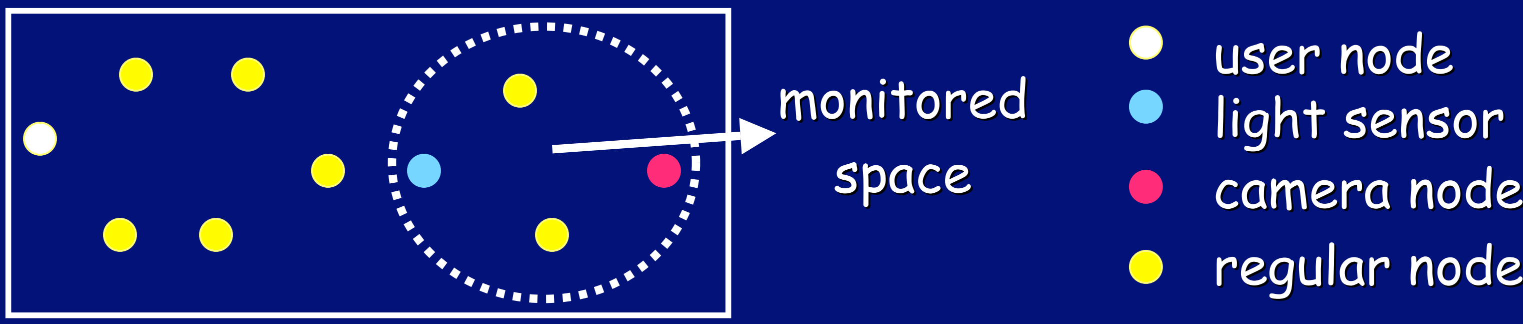
{Left_Hill,Hot,1} → {yU78GH5,location}

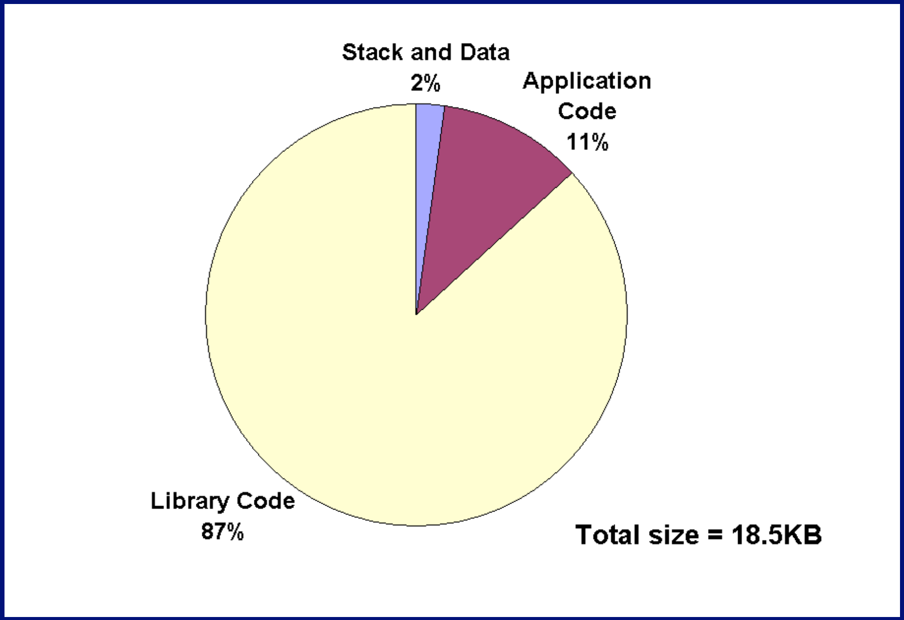
Code Brick

```
ret = migrate_geo(location, timeout);
if ret == LocationUnreachable
    ret = migrate_tag(yU78GH5,  timeout);
if (ret == OK) && (location == Left_Hill)
    return readTag(temp);
else throw TimeoutException
```

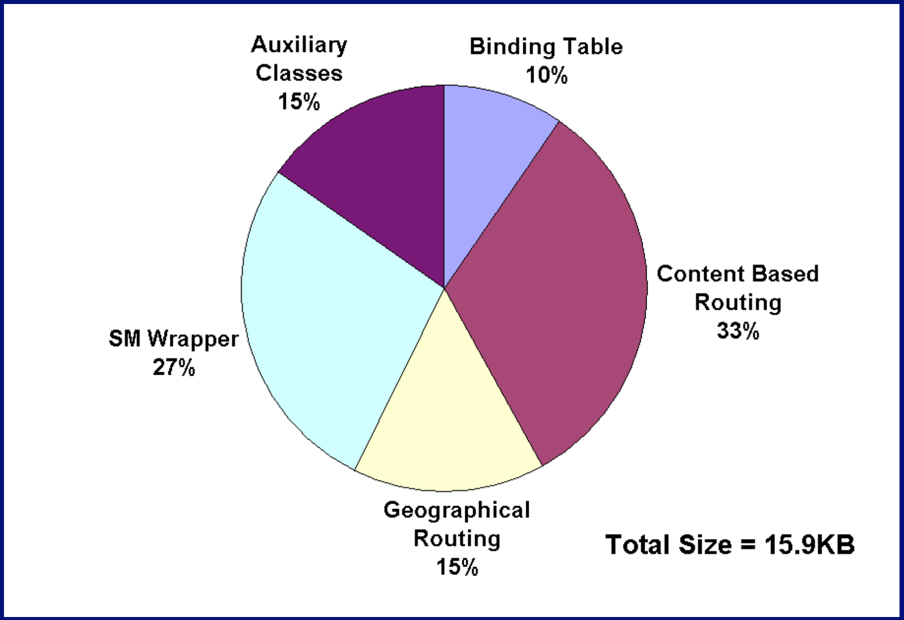
SP Application: Intrusion Detection

10 HP iPAQs with 802.11 cards and GPS devices



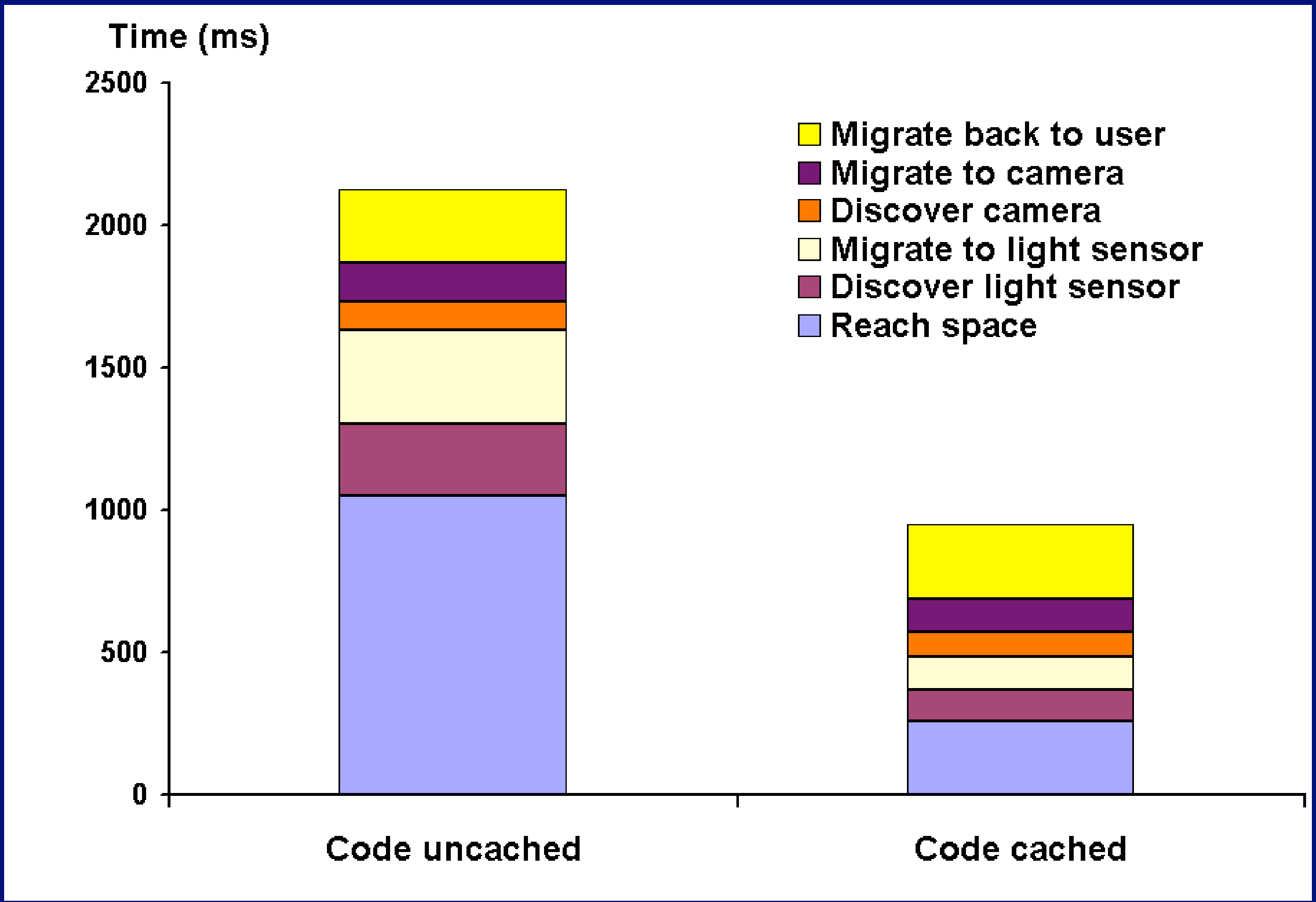


Code Size breakdown for SM (Application + SP Library)



Code Size breakdown for SP library

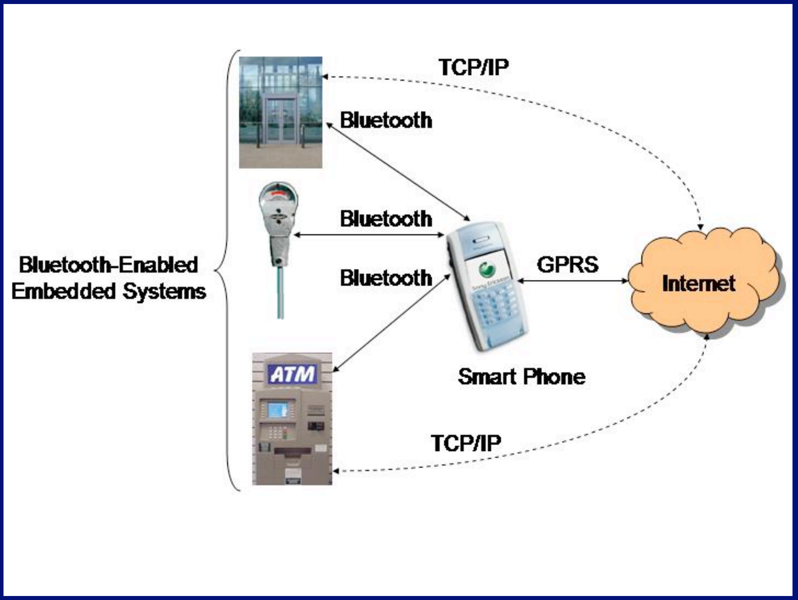
Execution Time Breakdown



Conclusions

- Spatial Programming makes outdoor distributed applications simple to program
- Volatility, mobility, configuration dynamics, ad-hoc networking are hidden from programmer
- Implementation on top of a Smart Messages
  - Easy to deploy new applications in the network
  - Quick adaptation to highly dynamic network configurations

Future Work: Real Applications



- EZCab: An automatic systems for booking cabs in cities
- TrafficView: A scalable traffic monitoring system
- Smiles: SmartPhones for interacting with local embedded systems

Thank you!

http://discolab.rutgers.edu

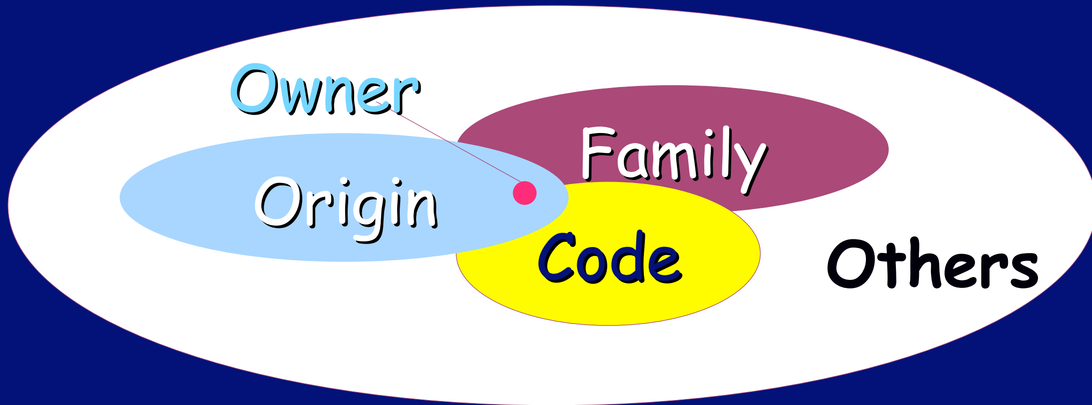
Outdoor Distributed Computing Project People:

Professor Liviu Iftode

Graduate Students: Cristian Borcea, Porlin Kang, Nishkam Ravi, Peng Zhou

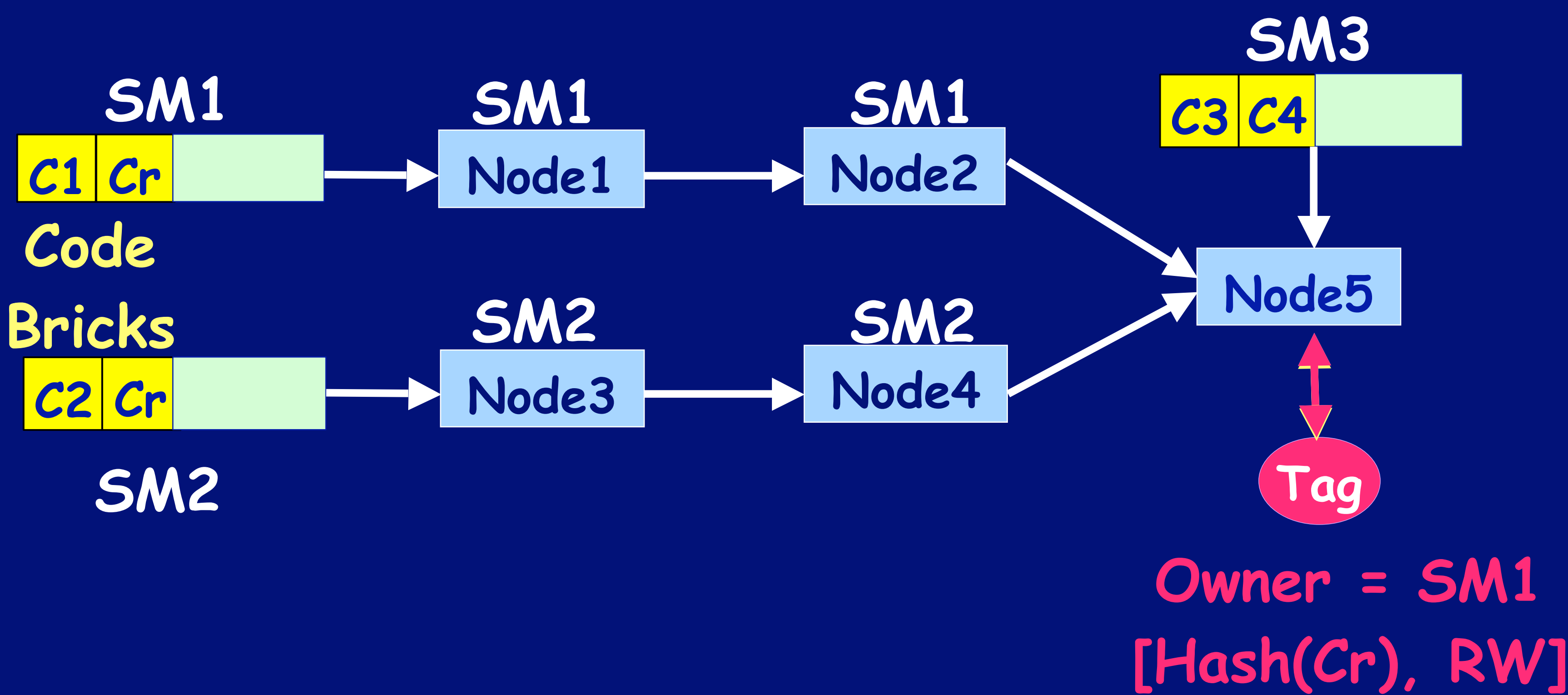
Collaboration with Professor Ulrich Kremer and Professor Chalermek Intanagonwiwat

Protection Domains for Tag Space



- Owner: SM that creates the tag
- Family: all SMs having a common ancestor with the SM that owns the tag
- Origin: all SMs created on the same node as the family originator of the tag owner
- Code: all SMs carrying a specific code brick
- Others: all the other SMs

Access Control Example (Code-based protection domain)



Cr Same routing used by SM1 and SM2

Access permission granted for SM2

Access permission denied for SM3