Thesis defense:

JiST – Java in Simulation Time

An efficient, unifying approach to simulation using virtual machines

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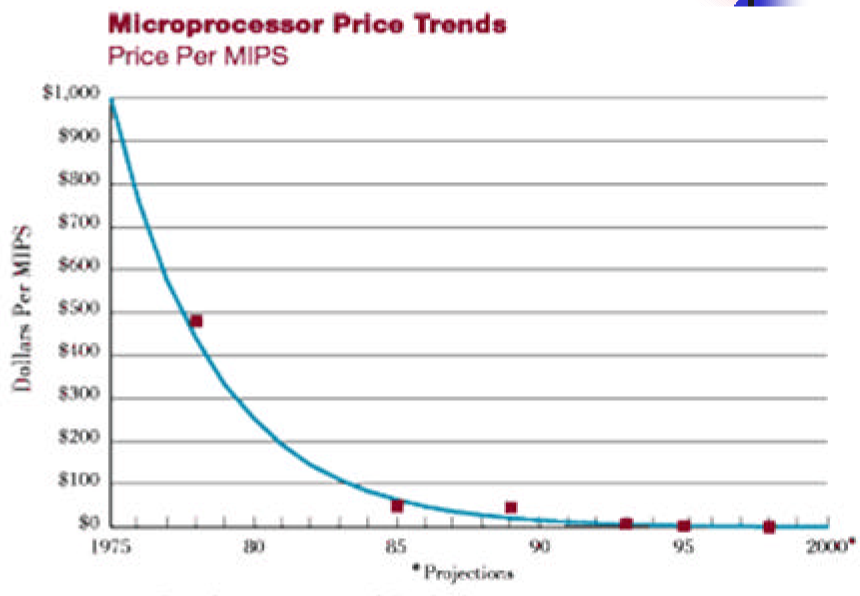
3 May 2004

http://www.cs.cornell.edu/barr/repository/jist/

motivation: simulation

- **cost per MIPS declining**
  - **e.g. Pentium Xeon:**
  - **~10,000 MIPS @ ~$200**



- **emphasis on computation**
  - **vs. analytical methods**
  - **vs. empirical methods**

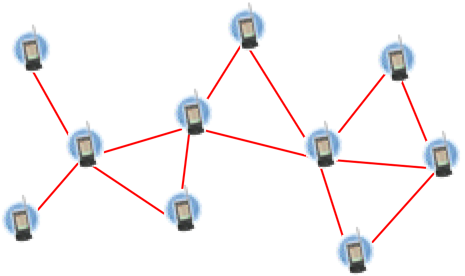
- **simulators are useful and needed**

  examples –
  - **physics: electron tunneling, star collisions, particle dynamics, …**
  - **biology: protein folding, disease spread, genetic drift, …**
  - **earth science: weather prediction, tectonic modeling, water quality, …**
  - **finance: portfolio pricing, statistical arbitrage, risk analysis, …**
  - **operations: optimize workflow, supply chain, inventory, pricing, …**
  - **CS: performance analysis of networks, processors, heuristics, …**
  - **… take any subject X, and google “X simulation”**

motivation: simulation scalability

- e.g., wireless networks
- published ad hoc network simulations
  - lack network size - ~500 nodes; or
  - compromise detail - packet level; or
  - curtail duration - few minutes; or
  - are of sparse density - <10/km^2

  i.e. limited simulation scalability [Riley02]



- wish to simulate
  - a university campus: 30,000 students
  - the U.S. military: 100-150,000 troops
  - sensor networks, smart dust, Ubicomp with hundreds of thousands of cheap wireless devices distributed across the environment

Simulation scalability is important

what is a simulation?

- unstructured simulation: computers compute
- time structured: event-oriented vs. process-oriented

- discrete event simulator is a program that:
  - encodes the simulation model
  - stores the state of the simulated world
  - performs events at discrete simulation times
  - loops through a temporally ordered event queue
  - works through simulation time as quickly as possible

- desirable properties of a simulator:

• correctness	- valid simulation results
• efficiency	- performance in terms of throughput and memory
• transparency	- separate correctness from efficiency: - write "simple" program in a standard language - provide implicit optimization, concurrency, distribution, portability, etc.

how do we build simulators?

systems

- simulation kernels
  - control scheduling, IPC, clock
  - processes run in virtual time
  - e.g. TimeWarp OS [Jefferson87], Warped [Martin96]

  👍 transparency 👎 efficiency

- simulation libraries
  - move functionality to user-space for performance; monolithic prog.
  - usually event-oriented
  - e.g. Yansl [Joines94], Compose [Martin95], ns2 [McCanne95]

  👎 transparency 👍 efficiency

languages

- generic simulation languages
  - introduce entities, messages and simulation time semantics
  - event and state constraints allow optimization
  - both event and process oriented
  - e.g. Simula [Dahl66], Parsec [Bagrodia98] / GloMoSim [Zeng98]
- application-specific languages
  - e.g. Apostle [Bruce97], TeD [Perumalla98]

◇? transparency ◇? efficiency

👍👎 new language

virtual machines

virtual machine-based simulation

- **Thesis statement:**

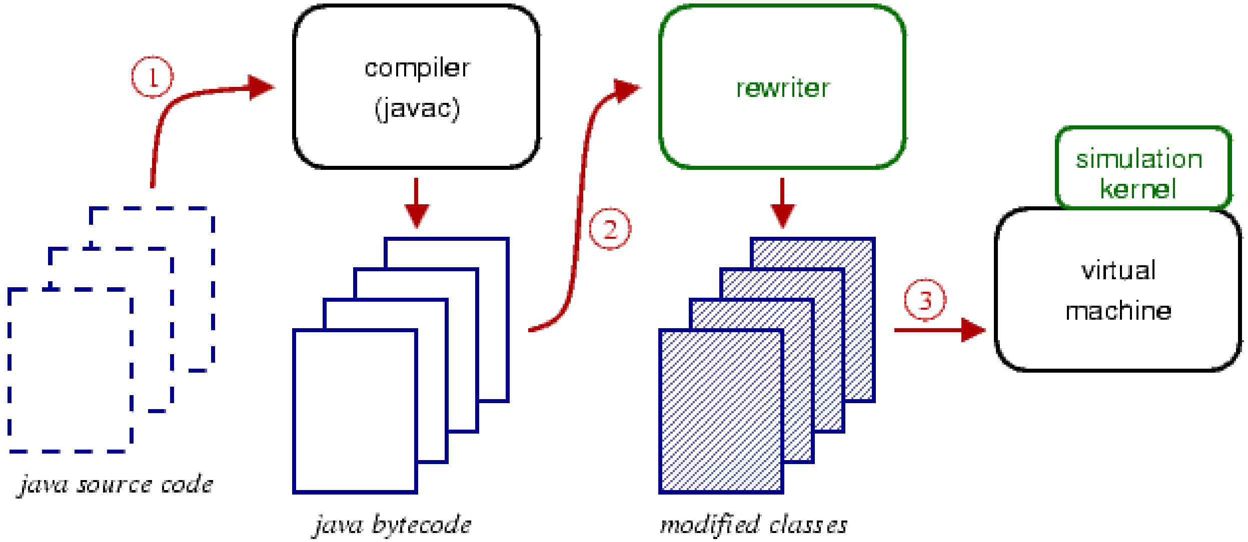
> **A virtual machine-based simulator benefits from the advantages of both the traditional systems and language-based designs by leveraging standard compilers and language runtimes as well as ensuring efficient simulation execution through transparent cross-cutting program transformations and optimizations.**

- **JiST – Java in Simulation Time**
  - **converts a virtual machine into a simulation platform**
  - **no new language, no new library, no new runtime**
  - **merges modern language and simulation semantics**
    - **combines systems-based and languages-based approaches**
    - **result: virtual machine-based simulation**

	kernel	library	language	**JiST**
transparent	++		++	++
efficient		+	+	++
standard	++	++		++

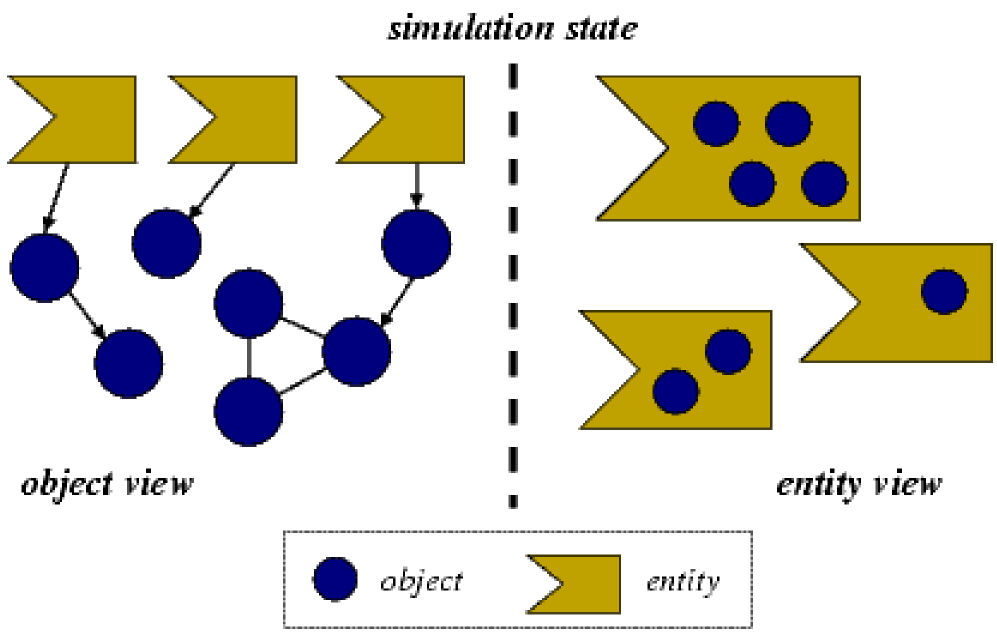
system architecture

1. **Compile simulation with standard Java compiler**
2. **Run simulation within JiST (within Java); simulation classes are dynamically rewritten to introduce simulation time semantics:**
   - **extend the Java object model and execution model**
   - **instructions take zero (simulation) time**
   - **time explicitly advanced by the program: `sleep(time)`**
   - **progress of time is dependent on program progress**
3. **Rewritten program interacts with simulation kernel**



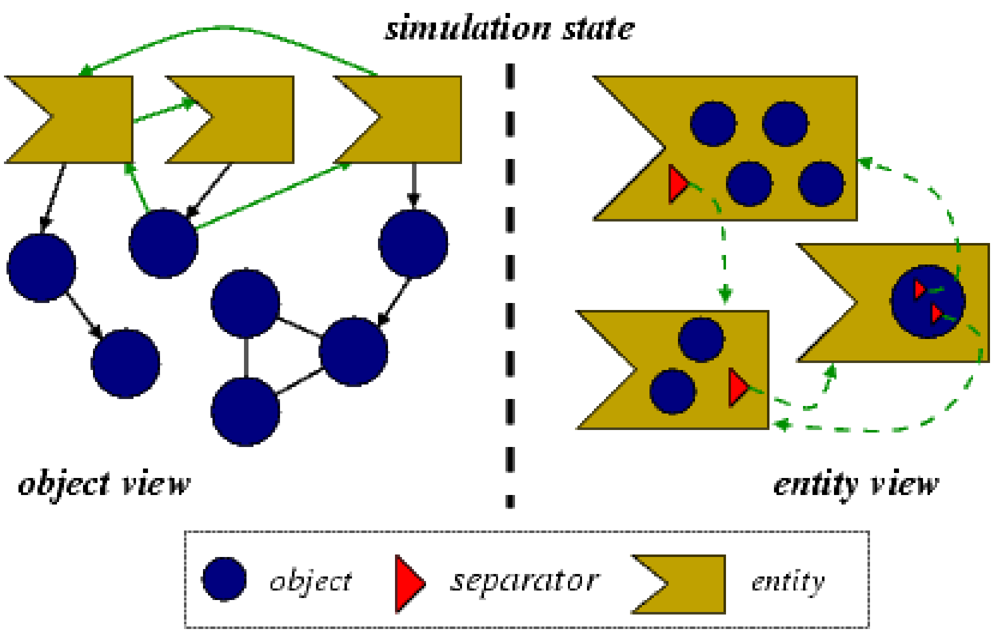
jist object model

- program state contained in objects
- objects contained in entities
  - think of an entity as a simulation component
  - an entity is any class tagged with the `Entity` interface
  - each entity runs at its own simulation time
  - as with objects, entities do not share state
  - akin to JKernel [Hawblitzel98] process in spirit, without the threads!



jist execution model

- entity methods are an event interface
  - simulation time invocation
  - non-blocking; invoked at caller entity time; no continuation
  - like co-routines, but scheduled in simulation time
- entity references replaced with separators
  - event channels; act as state-time boundary
  - demarcate a TimeWarp-like process, but at finer granularity



a basic example

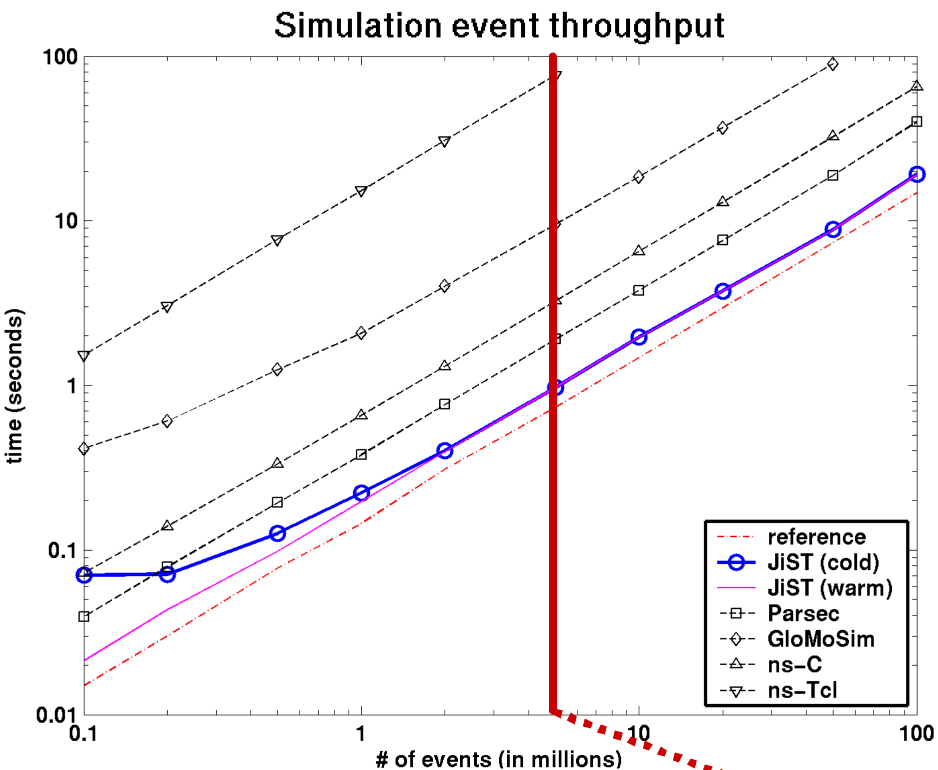
- the “hello world” of event simulations

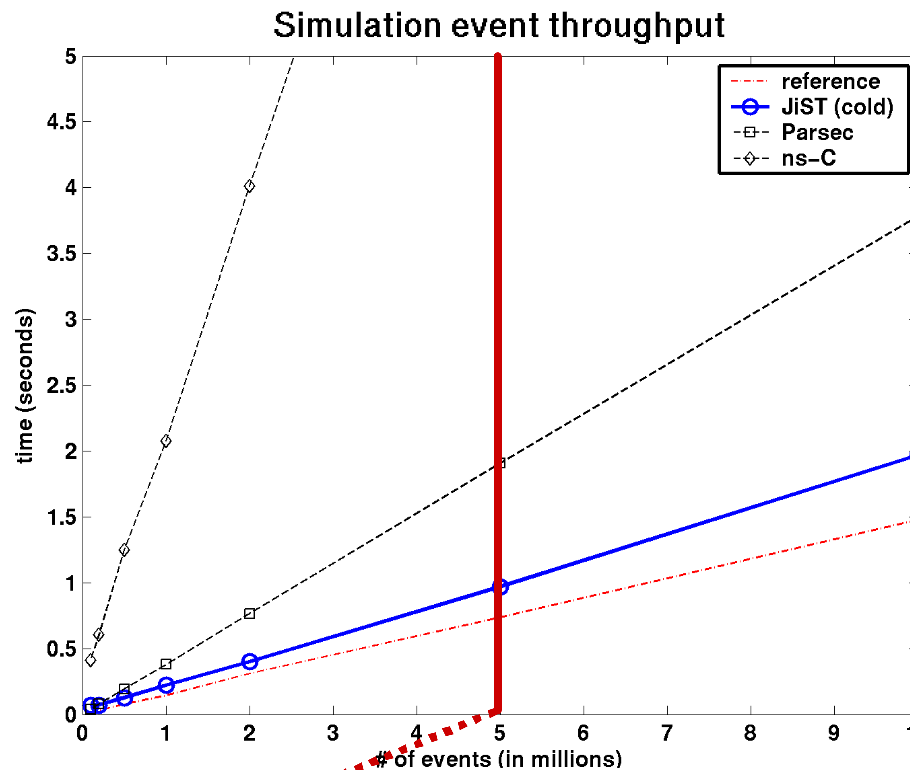
```
class HelloWorld implements JistAPI.Entity
{
  public void hello()
  {
    JistAPI.sleep(1);
    hello();
    System.out.println("hello world, " +
       "time=" + JistAPI.getTime() );
  }
}
```

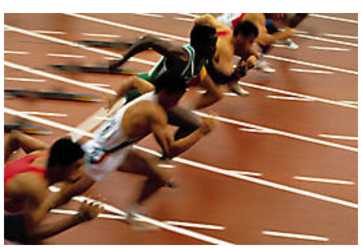
- demo!

Java	JiST
Stack overflow @hello	hello world, time=1 hello world, time=2 hello world, time=3 etc.

jist micro-benchmark: event throughput

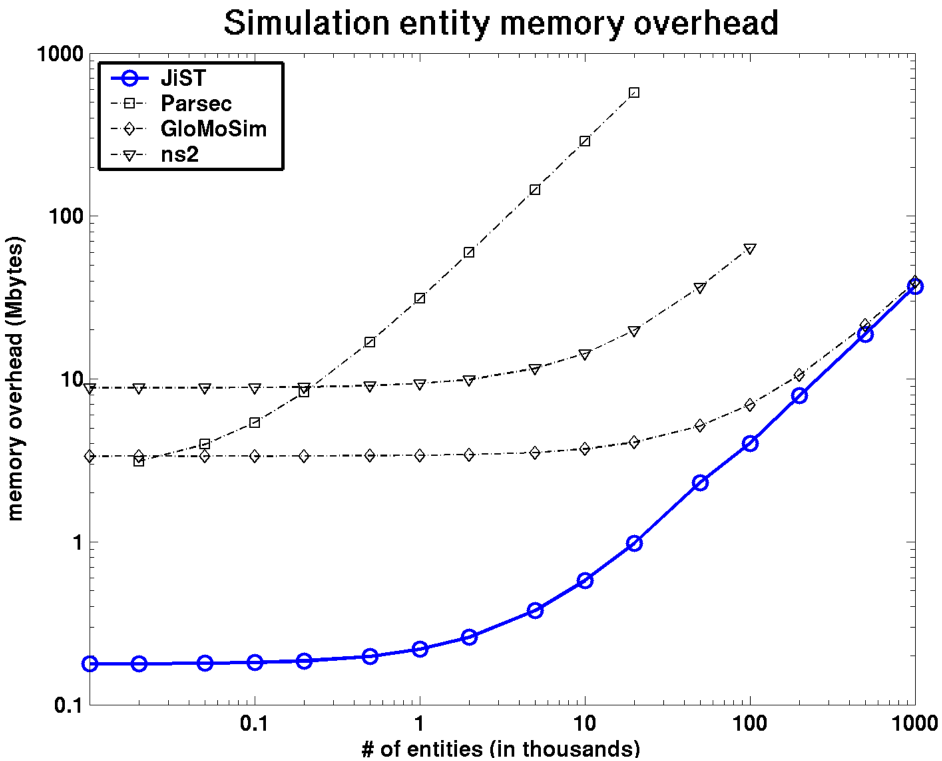


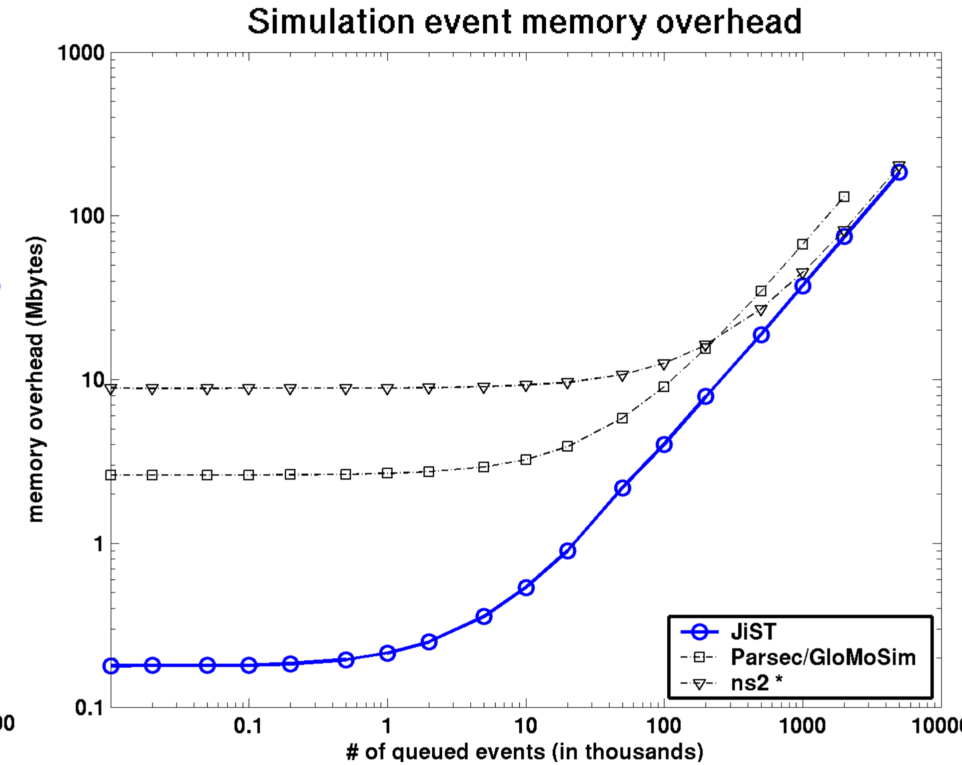




5x10^6 events	time (sec)	vs. reference	vs. JiST
reference	0.74		**0.76x**
JiST	**0.97**	1.31x	
Parsec	1.91	2.59x	**1.97x**
ns2-C	3.26	4.42x	**3.36x**
GloMoSim	9.54	12.93x	**9.84x**
ns2-Tcl	76.56	103.81x	**78.97x**

jist micro-benchmark: memory overhead

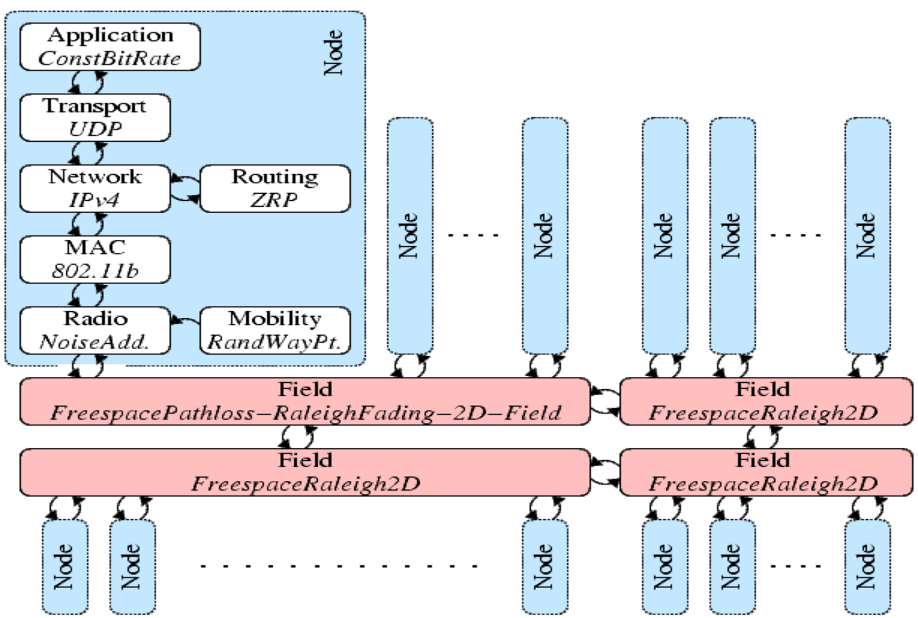


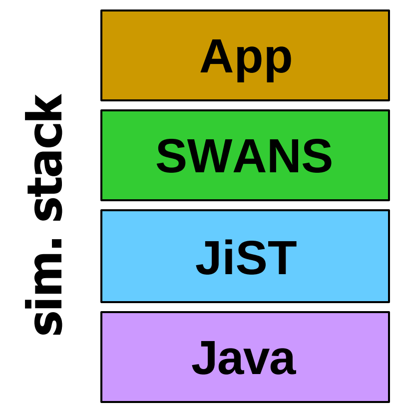


memory	per entity	per event	10K nodes sim.
JiST	**36 B**	**36 B**	**21 MB**
GloMoSim	36 B	64 B	35 MB
ns2 *	544 B	40 B	74 MB
Parsec	28536 B	64 B	2885 MB

SWANS

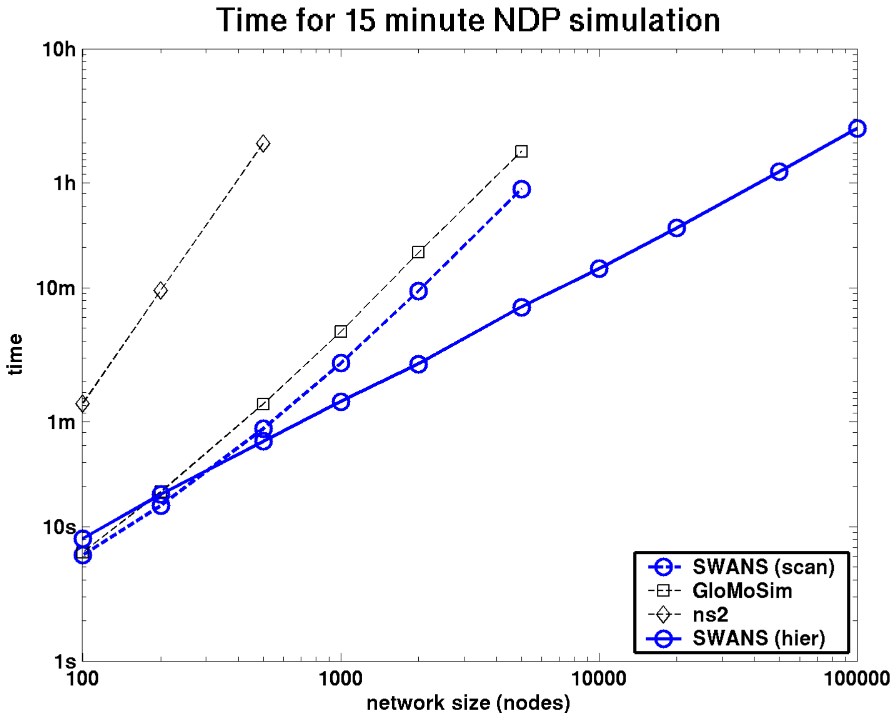
- **<u>S</u>calable <u>W</u>ireless <u>A</u>d hoc <u>N</u>etwork <u>S</u>imulator**
  - **similar functionality to ns2** [McCanne95] **and GloMoSim** [Zeng98]**, but...**
  - **runs standard Java network applications over simulated networks**
  - **can simulate networks of 1,000,000 nodes sequentially, on a single commodity uni-processor**
  - **runs on top of JiST; SWANS is a JiST application**
  - **uses hierarchical binning for efficient propagation**
  - **component-based architecture written in Java**

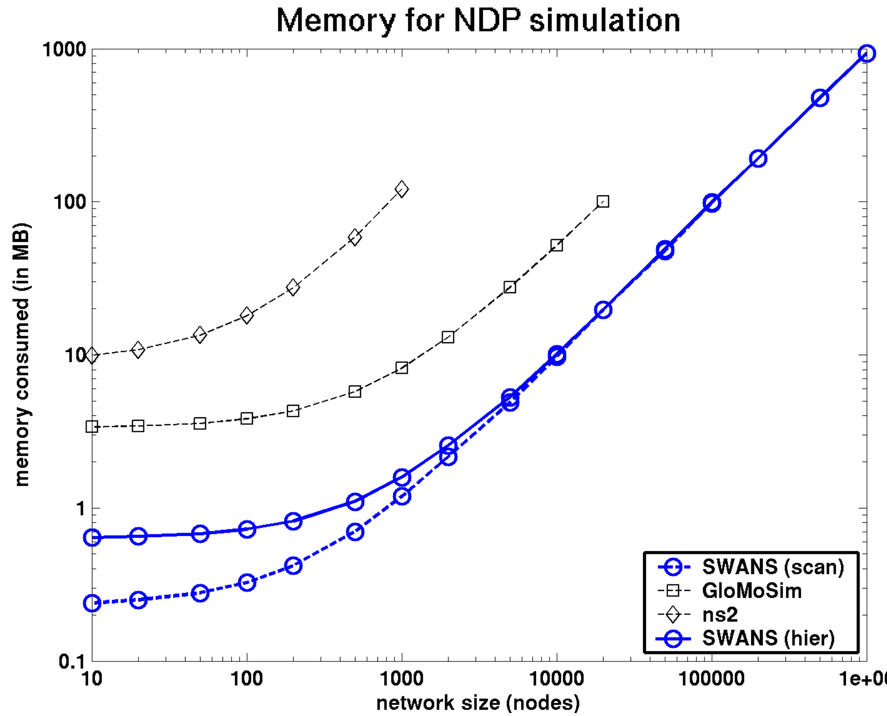




	files	classes	lines	semi
JiST	29	117	14256	3530
SWANS	85	220	29157	6586
Other	32	80	7204	2525
	146	**417**	**50617**	**12641**

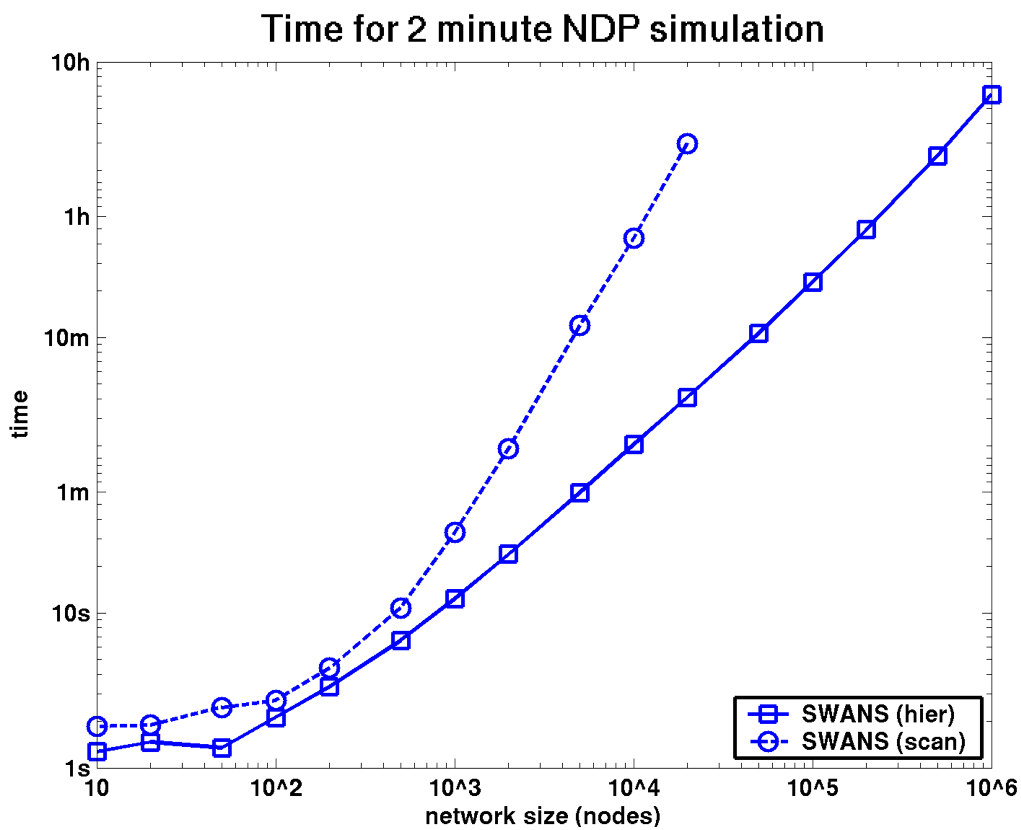
SWANS performance





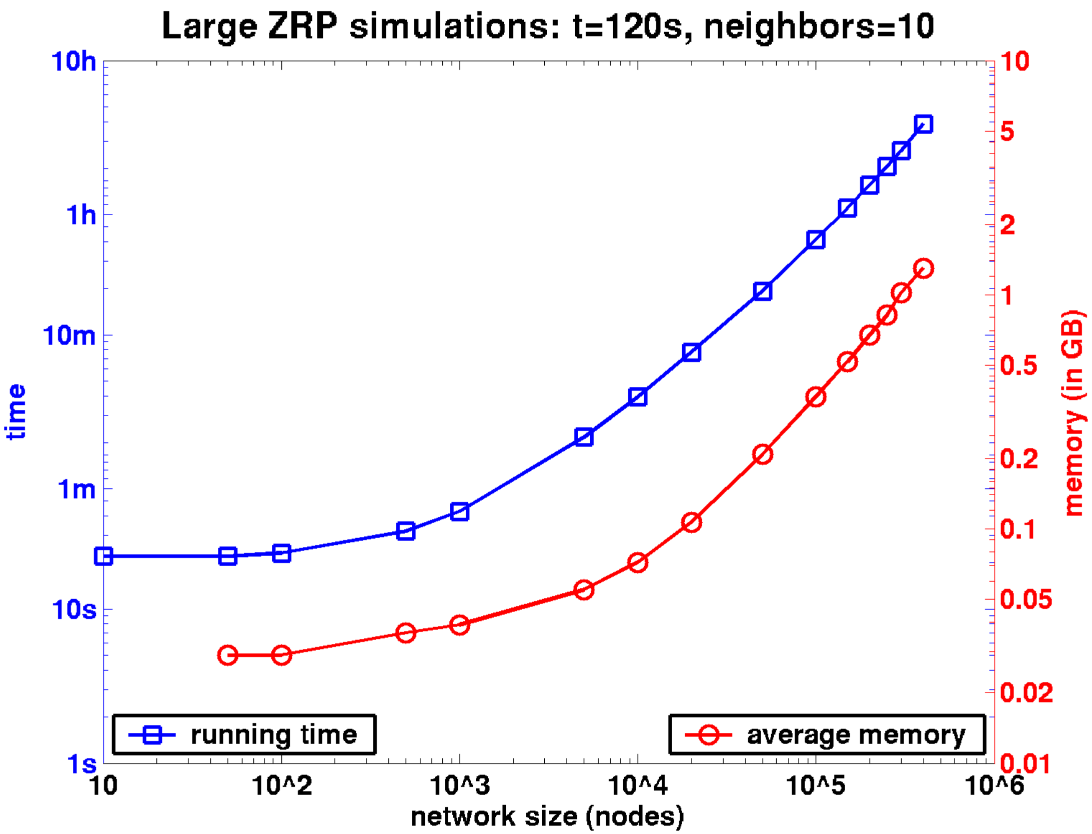
t=15m	ns2		GloMoSim		SWANS		SWANS-hier	
nodes	**time**	**memory**	**time**	**memory**	**time**	**memory**	**time**	**memory**
500	7136.3 s	**58761 KB**	81.6 s	5759 KB	53.5 s	700 KB	***43.1 s***	1101 KB
5000			**6191.4 s**	**27570 KB**	**3249.6 s**	4887 KB	***433.0 s***	5284 KB
50000						**47717 KB**	***4377.0 s***	**49262 KB**

SWANS performance



t=2m	SWANS-hier NDP simulation			
nodes	10,000	100,000	**1 million**	**per node**
initial memory	13 MB	100 MB	**1000 MB**	**1.0 KB**
avg. memory	45 MB	160 MB	**1200 MB**	**1.2 KB**
time	2 m	25 m	**5.5 h**	**20 ms**

SWANS performance



t=2m	SWANS-hier ZRP simulation			
nodes	10,000	100,000	**500,000**	**per node**
avg. memory	72 MB	367 MB	**1630 MB**	**3.3 KB**
time	4 m	41 m	**290 m**	**35 ms**

Recent network research results:

- Analyzed cost of route discovery in large ad hoc networks.
- Showed that the bordercast protocol performance is independent of node density, proven to be optimal.
- Bordercast can improve performance of many existing flooding-based routing protocols.
- Optimal bordercast performance at zone radii = 2 hops.
- Cost of zone maintenance bounded, proportional to network mobility.
- Aggregating link state zone updates substantially reduces maintenance overhead.

benefits of the jist approach

more than just performance…

- **application-oriented benefits**

type safety	source and target statically checked
event types	not required (implicit)
event structures	not required (implicit)
debugging	dispatch source location and state available

- **language-oriented benefits**

Java	standard language, compiler, runtime
garbage collection	cleaner code, memory savings
reflection	script-based simulation configuration
safety	fine grained isolation
robustness	no memory leaks, no crashes

- **system-oriented benefits**

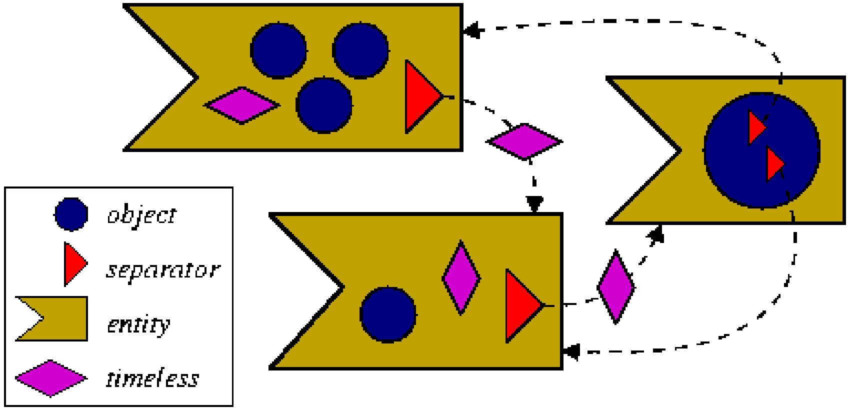
IPC	no context switch, no serialization, zero-copy
Java kernel	cross-layer optimization
rewriting	no source-code access required, cross-cutting program transformations and optimizations
distribution	provides a single system image abstraction
concurrency	model supports parallel and speculative execution

- **hardware-oriented benefits**

cost	COTS hardware and clusters
portability	runs on everything

zero-copy semantics

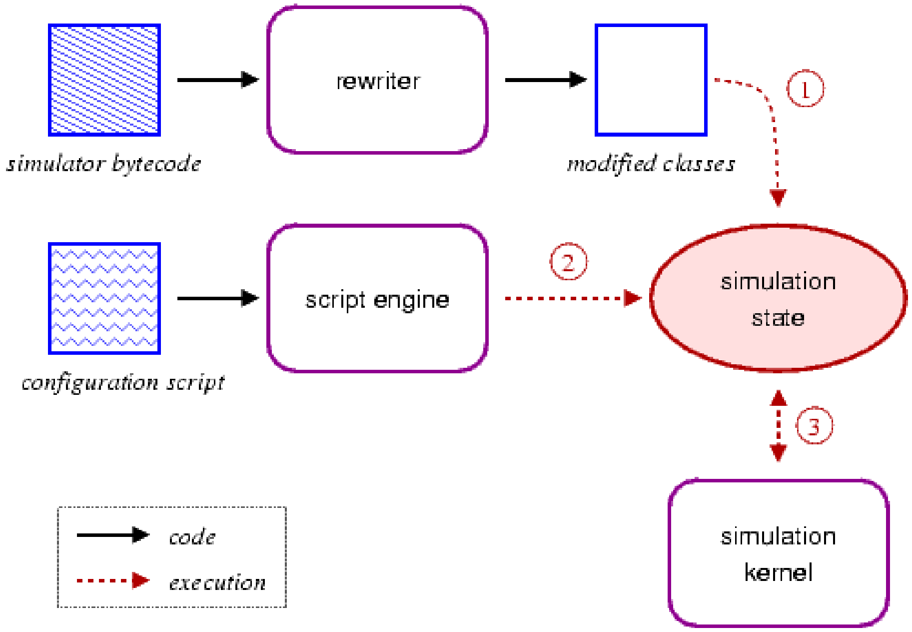
- timeless object: a temporally stable object
  - inferred statically as open-world immutable
  - or tagged explicitly with the `Timeless` interface
- benefits
  - pass-by-reference saves memory copy
    - zero-copy semantics for inter-entity communication
  - saves memory for common shared objects
    - e.g. broadcast network packets
    - rewrite `new` of common types to `hashcons`



configurability

- **configurability is essential for simulators**
  1. **source level reuse; recompilation**
  2. **configuration files read by driver program**
  3. **driver program is a scripting language engine**

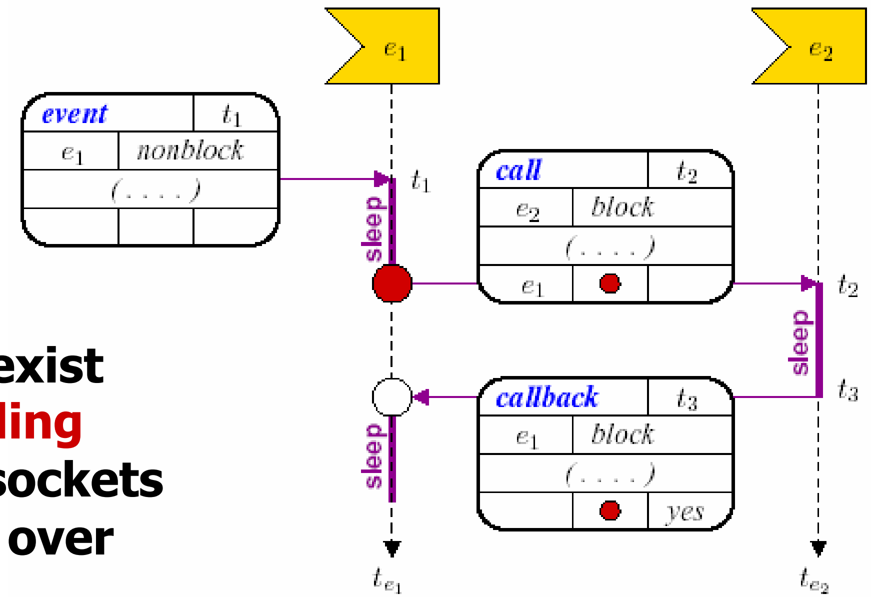
- **support for multiple scripting languages by reflection**
  - **no additional code**
  - **no memory overhead**
  - **no performance hit**
  - **Bsh - scripted Java**
    Jython - Python
  - **Smalltalk, Tcl, Ruby, Scheme and JavaScript**



process-oriented simulation

- using entity method invocations…
  - one can easily write **event-driven** entities.
  - what about **process-oriented** simulation?

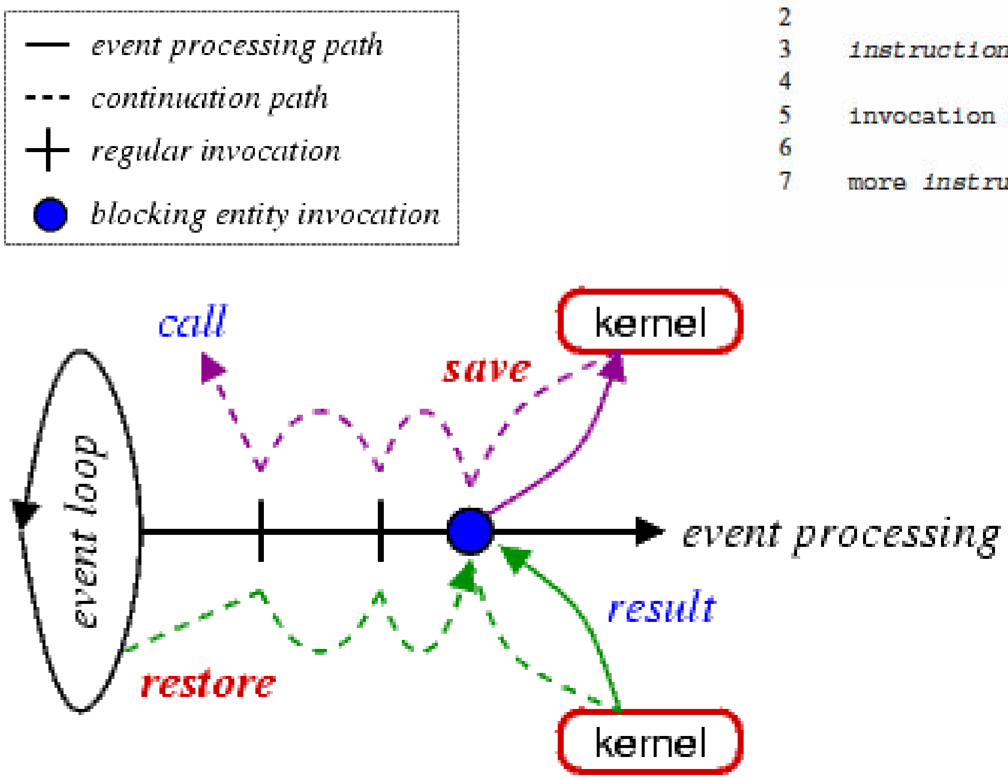
- **blocking events**
  - any entity method that “throws” a `Continuation` exception
  - event processing frozen at invocation
  - continues after call event completes, at some later simulation time



- benefits
  - no explicit process
  - blocking and non-blocking coexist
  - akin to **simulation time threading**
  - can build simulated network sockets
  - can **run standard applications** over these simulated sockets

capturing continuations

- **mark entity method as blocking: `throws Continuation`**
- **saving and restoring the stack is non-trivial in Java!**



Before CPS transform:

```
METHOD continuable:

  instructions

  invocation BLOCKING

  more instructions
```

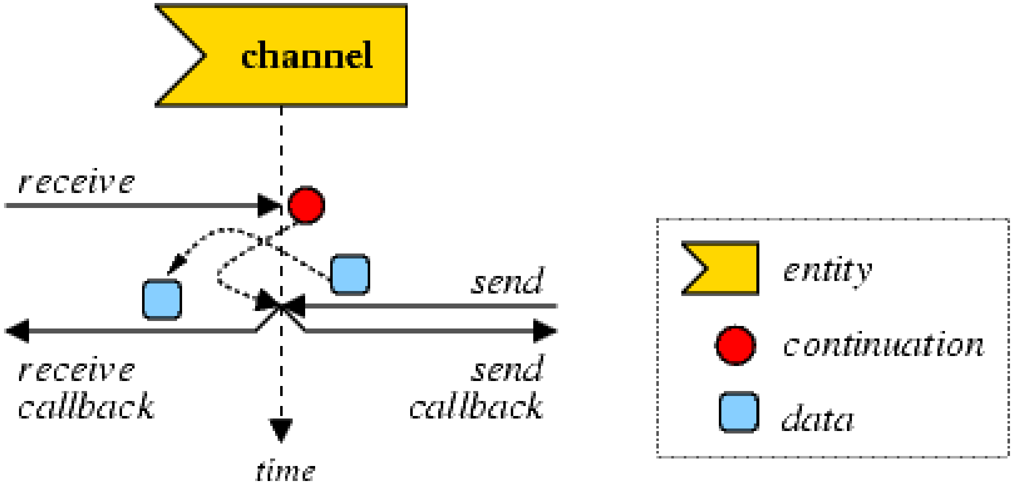
After CPS transform:

```
METHOD continuable:
  if jist.isRestoreMode:
    jist.popFrame f
    switch f.pc:
      case PC1:
        restoreLocals f.locals
        restoreStack f.stack
        goto PC1
      ...

  instructions

  setPC f.pc, PC1
  saveLocals f.locals
  saveStack f.stack
PC1:
  invocation BLOCKING
  if jist.isSaveMode:
    jist.pushFrame f
    return

  more instructions
```

simulation time concurrency

using continuations…

- **simulation time `Thread`**
  - **cooperative concurrency**
  - **can also support pre-emptive, but not necessary**
- **simulation time concurrency primitives:**
  - **CSP Channel [Hoare78]: `JistAPI.createChannel()`**
  - **locks, semaphores, barriers, monitors, FIFOs, …**



rewriter flexibility

- **simulation time transformation**
  - extend Java object model with entities
  - extend Java execution model with events
  - language-based simulation kernel

- **extensions to the model**
  - **timeless objects:** pass-by-reference to avoid copy, saves memory
  - **reflection:** scripting, simulation configuration, tracing
  - **tight event coupling:** cross-layer optimization, debugging
  - **proxy entities:** interface-based entity definition
  - **blocking events:** call and callback, CPS transformation, standard applications
  - **simulation time concurrency:** Threads, Channels and other synch. primitives
  - **distribution:** location independence of entities, single system image abstraction
  - **parallelism:** concurrent and speculative execution
  - **orthogonal additions, transformations and optimizations**

- **platform for simulation research**
  - **e.g. reverse computations in optimistic simulation [Carothers99]**
  - **e.g. stack-less process oriented simulation [Booth97]**

summary

- **JiST – Java in Simulation Time**
  - **prototype virtual machine-based simulation platform**
  - **merges systems and language-based approaches**

	kernel	library	language	**JiST**
transparent	++		++	++
efficient		+	+	++
standard	++	++		++

  - **runs SWANS: Scalable Wireless Ad hoc Network Simulator**
  - **efficient: both in terms of throughput and memory**
  - **flexible: timeless objects, reflection-based scripting, tight event coupling, proxy entities, continuations and blocking methods, simulation time concurrency, distribution, concurrency … serve as a research platform**

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THANK YOU.

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