Jupiter: A Modular and Extensible JVM Infrastructure

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Motivation: Research into Scalable JVMs

- Jupiter project research goal: to investigate JVM architectures to deliver high performance on large-scale parallel systems.
  - 128-processor cluster of workstations with software-based SVM.
  - Single system image (SSI).
- To explore different approaches, we need a JVM infrastructure that is *Modular*, *Flexible*, and *Efficient.*
- Currently available JVMs:
  - Hard to modify (Kaffe, Sun's JDK).
  - Designed to explore a specific portion of JVM design space (Jalapeño, OpenJIT, Joeq, etc.).
- Hence, we elected to build our own infrastructure: The Jupiter JVM.
  - Hard.
  - Rewarding.

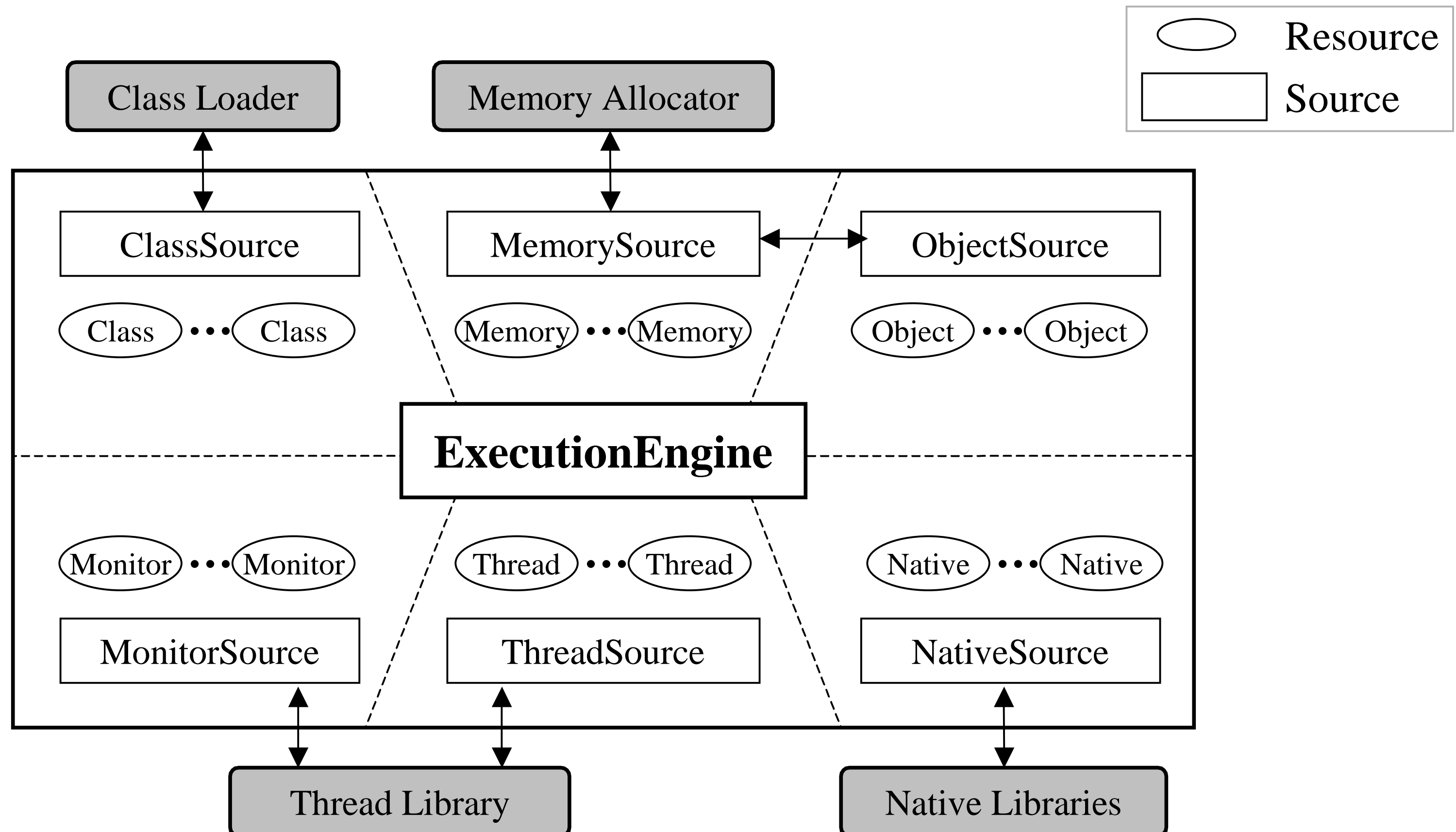
Outline

- Philosophy and architecture.
- Design techniques.
  - Flexibility.
  - Performance.
- Experimental evaluation.
- Conclusions and future work.

The Jupiter JVM Framework

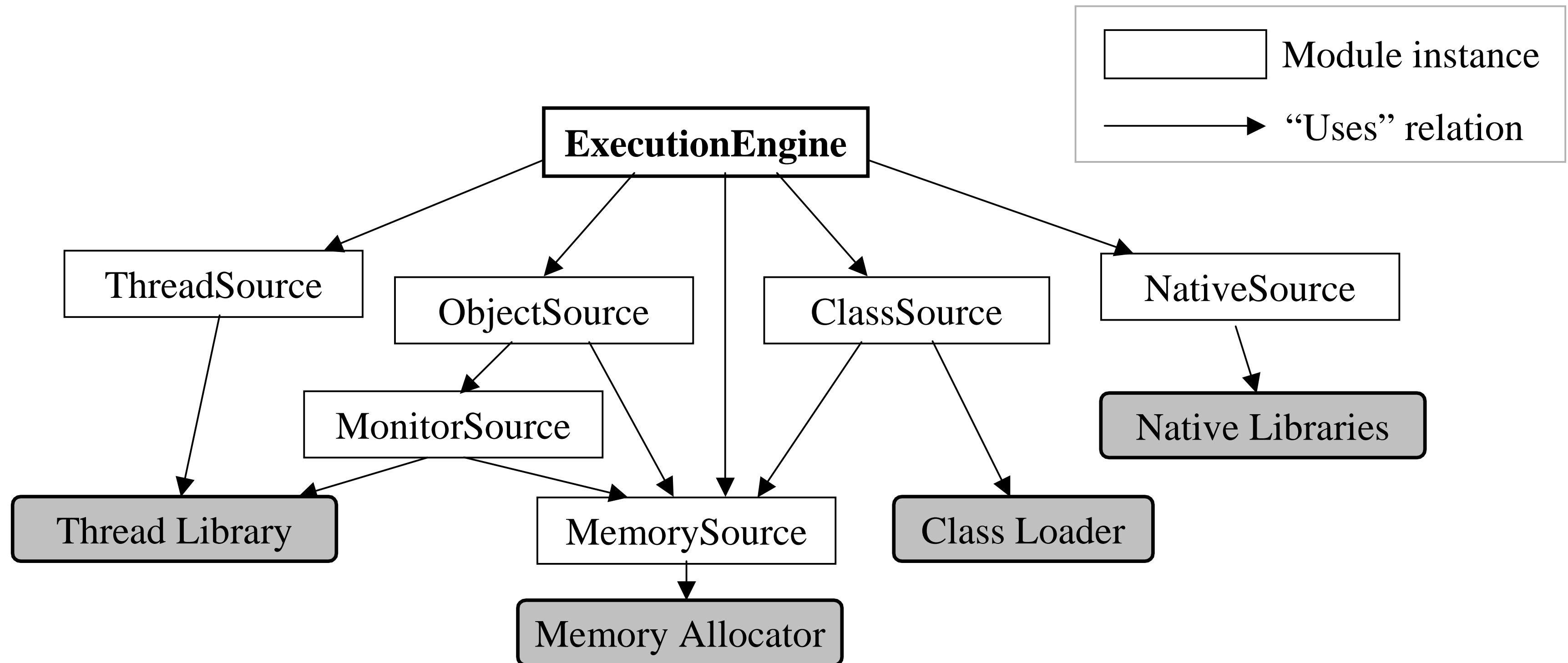
- Flexible design.
  - Modular components.
  - Object-oriented building-block architecture.
- Functional JVM.
  - Multi-threaded interpreter.
  - Executes the SPECjvm98 benchmarks.
  - Interfaces to Classpath library and Boehm garbage collector.
  - Currently no bytecode verifier and no JIT compiler.
- Competitive performance on SPECjvm98.
  - 2.65 times faster than Kaffe.
  - 2.20 times slower than Sun’s JDK.
  - Suitable for research on JVM scalability and performance issues.

Jupiter Overview



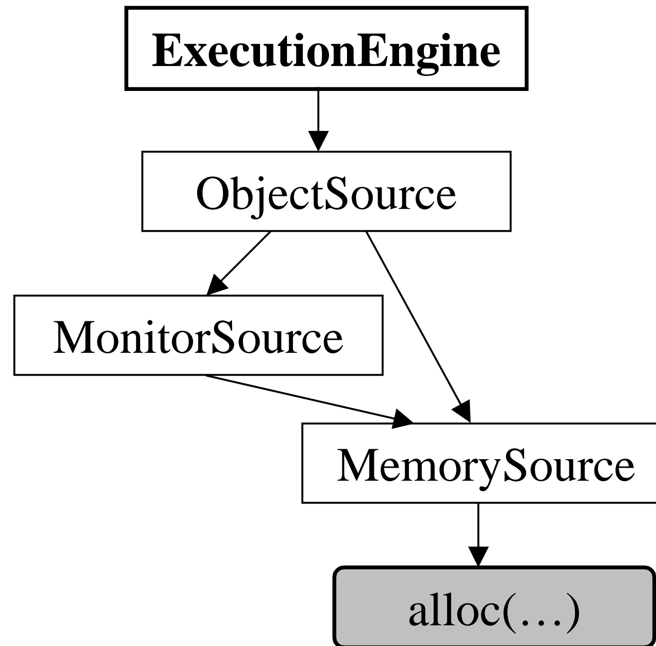
- Resources: items used by a running Java program.
- Sources: allocate and/or manage a resource.

An Incarnation of Jupiter



- Building-block architecture.
  - A JVM is assembled by interconnecting modules.
  - Nature of interconnections determines behaviour of JVM.

Object Allocator Example

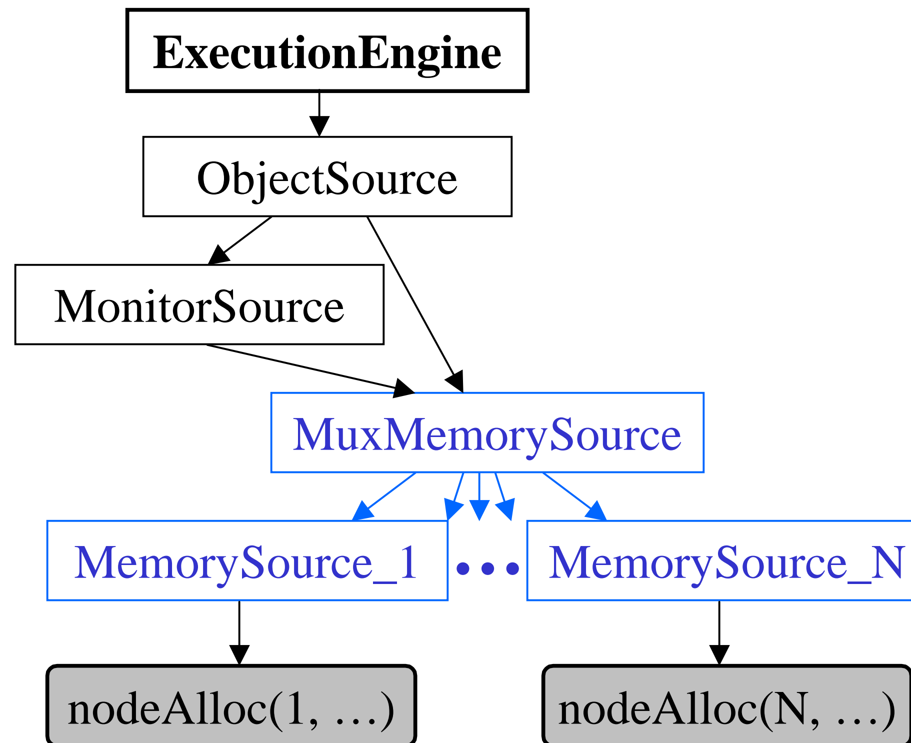


- Extend for NUMA multiprocessors:

```
void *nodeAlloc(int nodeNumber, int size);
```

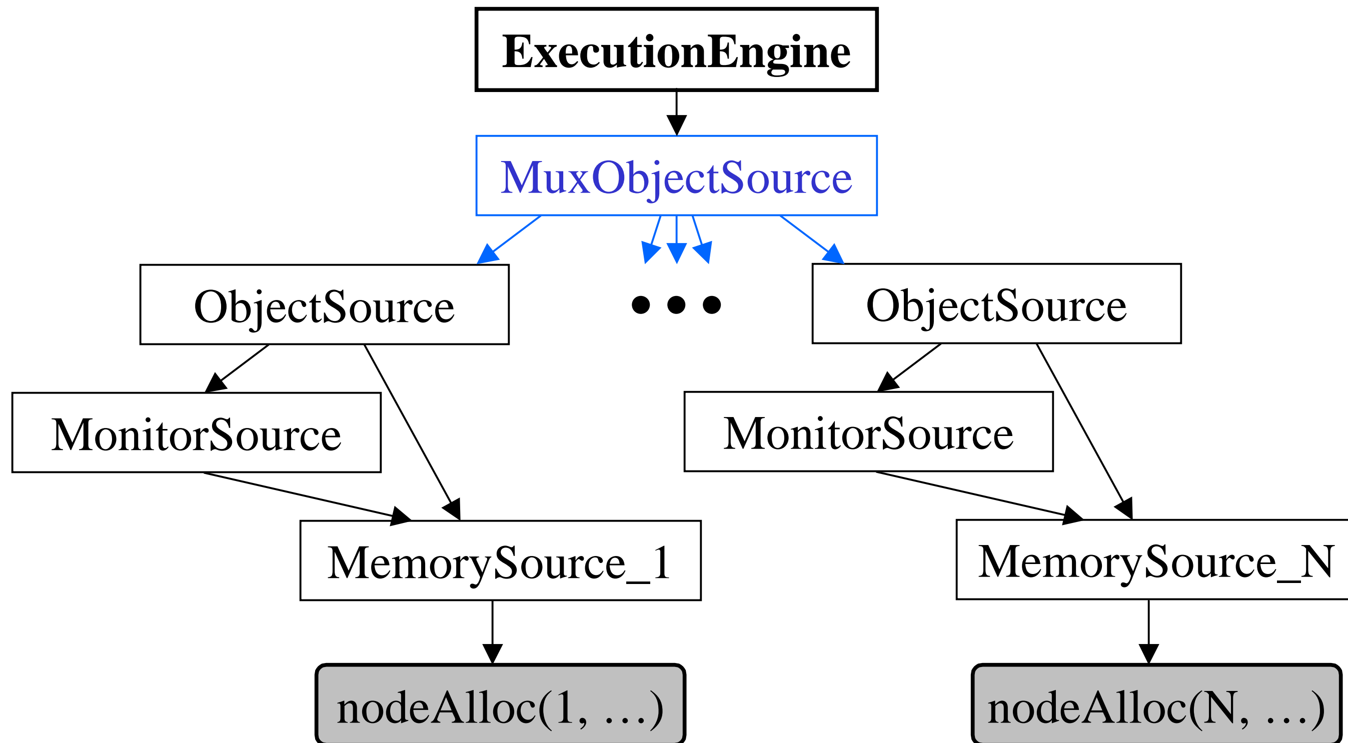
- Multiple levels:
  - Memory allocation level.
  - Object allocation level.
  - Execution engine level.

Node-specific MemorySources



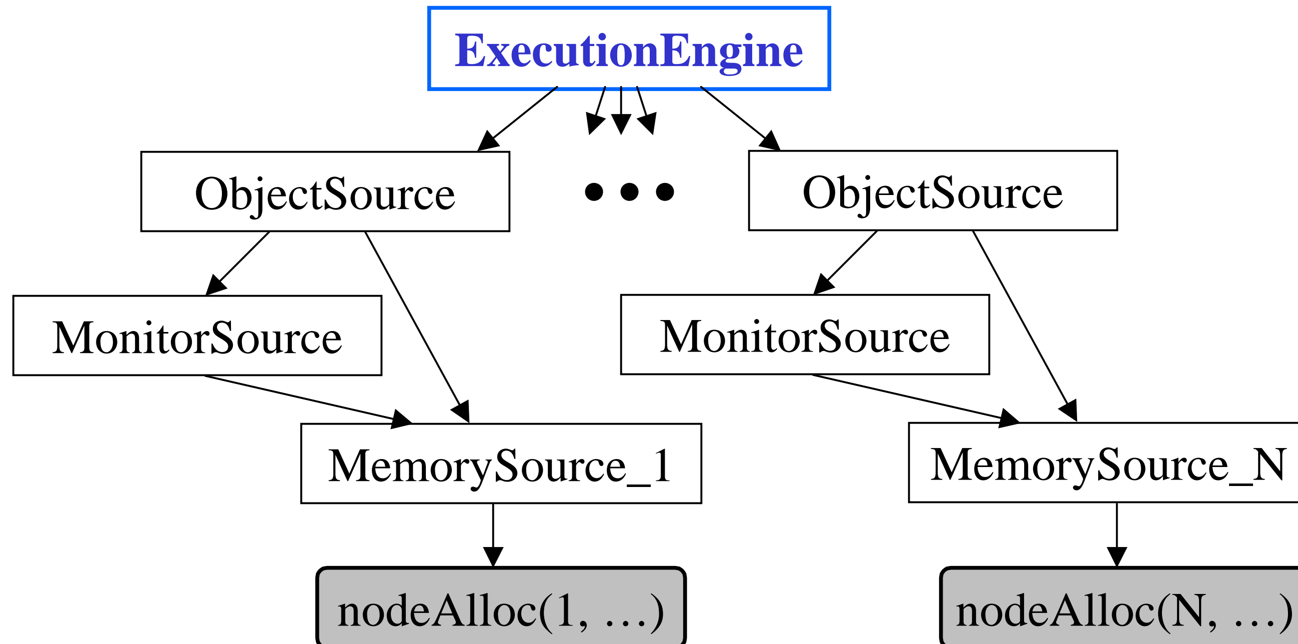
- MemorySource for each node.
  - Minimal change to the implementation of MemorySource.
  - Locality decisions made transparently in MuxMemorySource.
  - Same MemorySource interface.

Node-Specific ObjectSources



- ObjectSource for each node.
  - Enhances locality without altering ObjectSource interface.
  - Node choices still transparent to **ExecutionEngine**.
  - Same ObjectSource, MonitorSource, MemorySource_*i* as before.

A Locality-Aware ExecutionEngine



- Locality-aware **ExecutionEngine**.
  - **ExecutionEngine** directly manages locality.
  - Same ObjectSource, MonitorSource, MemorySource_*i* as before.
  - Modifications confined to **ExecutionEngine**.

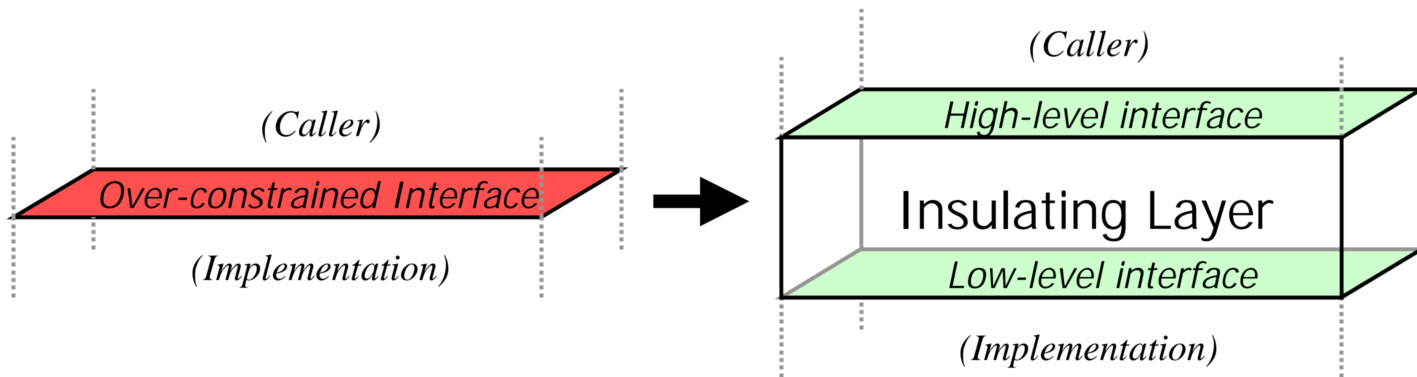
Design for Flexibility

- Flexibility achieved by applying many design techniques.
  - Interface coding conventions
  - Design by Contract
  - Splitting over-constrained interfaces
  - Modularity by maintenance characteristics
  - Pervasive error handling

- Example: **Splitting over-constrained interfaces.**

Over-constrained Interfaces

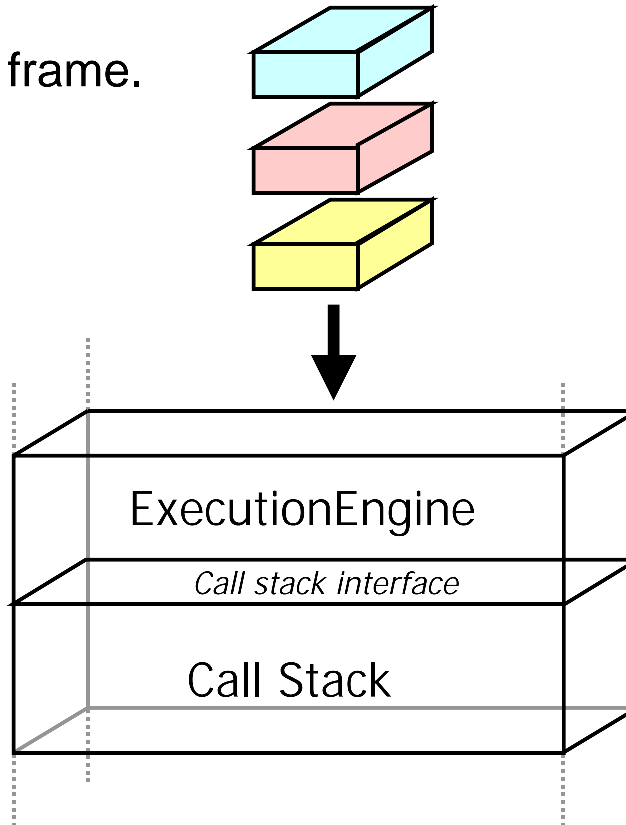
- Interface: the means by which pairs of modules communicate.
- Modules impose requirements on interfaces.
- Over-constrained interface: no design meets all requirements.
  - Requires modules to compromise.
  - Trade-offs impair flexibility.
- Solution: split the over-constrained interface into two.



- Insulating layer relieves each interface from the other's constraints.

Example: Call Stack Bookkeeping

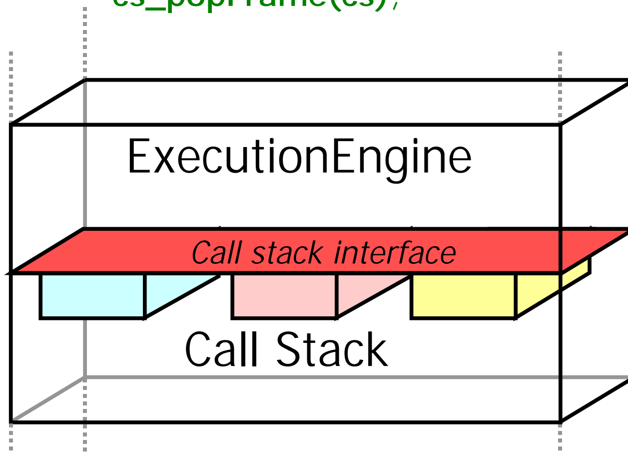
- One frame for each method pending execution.
  - A frame is “pushed” when a method is invoked.
  - A frame is “popped” when a method returns.
- Bookkeeping:
  - Keeping track of current top frame.
  - Propagating return value.
  - Synchronization.
- Whose responsibility?



Example: Call Stack Bookkeeping

Method invocation:

```
cs_pushFrame(cs, method);
 ...
cs_popFrame(cs);
```



cs_pushFrame(cs, method):

```
nextFrame = curFrame + methodFrameSize(method);
nextFrame->prev = cs->curFrame;
cs->curFrame = nextFrame;
if(isSynchronized(method))
   mn_enter(mbMonitor(method, curFrame));
```

cs_popFrame(cs):

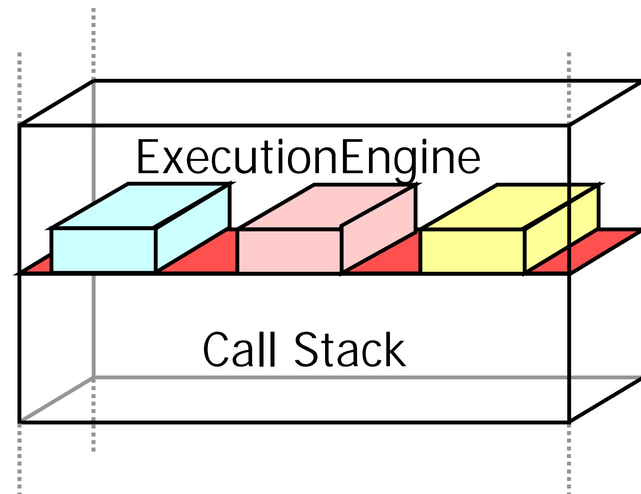
```
if(isSynchronized(method))
   mn_enter(mbMonitor(method, curFrame));
Value result = fr_pop(cs->curFrame);
cs->curFrame -=
   methodFrameSize(fr_method(curFrame));
fr_push(cs->curFrame, result);
```

Complicated!

Method invocation:

```
nextFrame = cs_getFrame(cs, method, curFrame);
nextFrame->prev = curFrame;
curFrame = nextFrame;
if(isSynchronized(method))
   mn_enter(mbMonitor(method, curFrame));

 ...
if(isSynchronized(method))
   mn_exit(mbMonitor(method, curFrame));
Value result = fr_pop(curFrame);
curFrame = curFrame-> prev;
fr_push(curFrame, result);
```

Complicated!



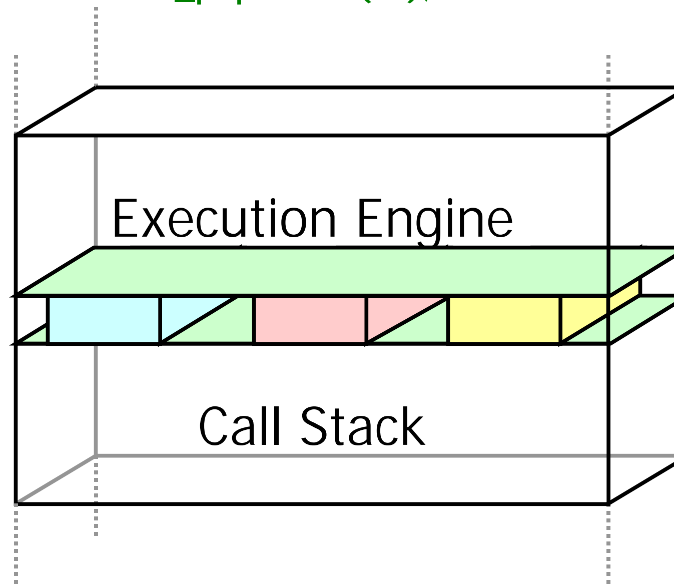
cs_getFrame(cs, method, curFrame):

```
return curFrame + methodFrameSize(method);
```

Example: Call Stack Bookkeeping

Method invocation:

```
cx_pushFrame(cx, method);
  ...
cx_popFrame(cx);
```



frs_getFrame(frs, method, curFrame):

```
return curFrame + methodFrameSize(method);
```

- Insulating layer makes both sides of the interface simpler.
- Small flexibility improvements accumulate.

Design for Performance

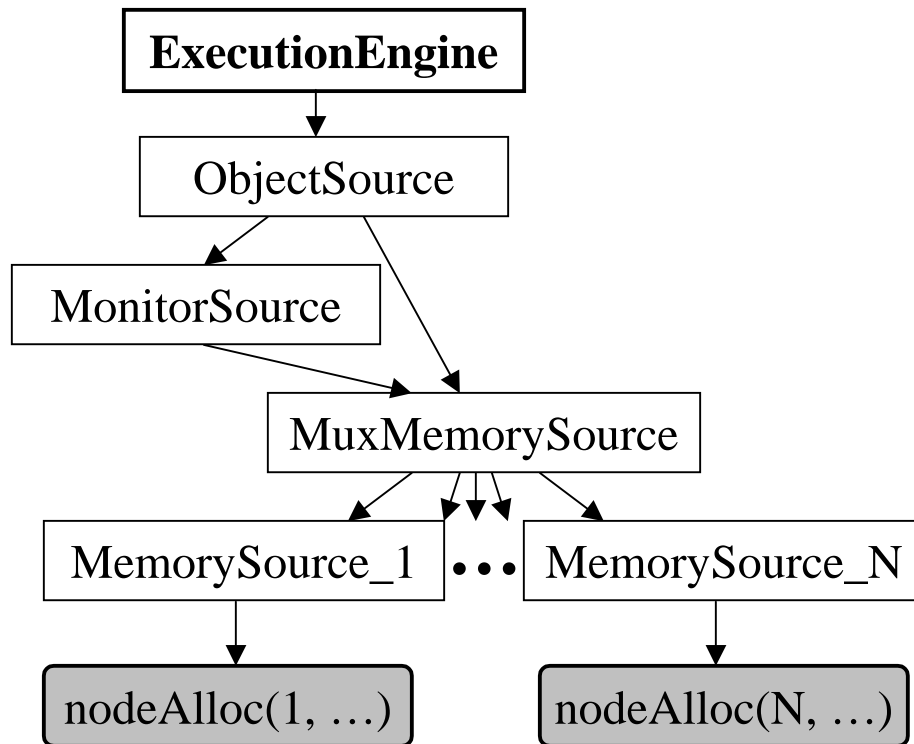
- Performance achieved by applying many design techniques.
  - Design by Contract
  - Lazy computation
  - Reducing arithmetic implied by interfaces
  - Promoting function inlining
  - Exploiting immutability

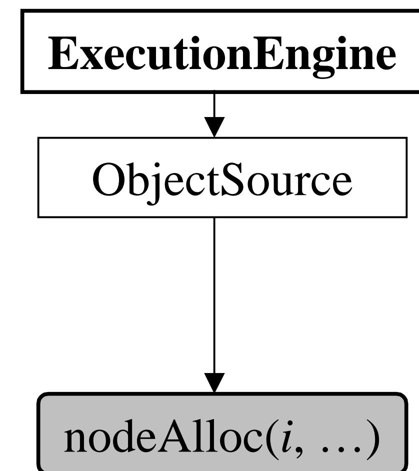
- Example: **Exploiting immutability.**

Exploiting Immutability

- **Immutable data**: never changes after construction.
  - Easily cached.
  - Freely duplicated.
  - Passed by value or reference.
  - No consistency problems among multiple copies.
- Therefore, Jupiter's data is immutable whenever practical.
- Immutable data provides opportunities for efficient implementation.

Example: Locality-aware Memory Allocation





- Two problems:
  - Call overhead: must make calls through the object hierarchy.
  - Object proliferation: MemorySource_i for each node i.

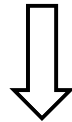
Example: Locality-aware Memory Allocation

- Custom declarations exploiting immutability of node number:

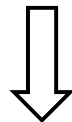
```
typedef int MemorySource;

inline MemorySource ms_new(int nodeNumber){
    return nodeNumber;
}

inline MemorySource ms_newMux(){ return -1; }

inline void *ms_getMemory(MemorySource this, int size){
    if(this == ms_newMux())
        return nodeAlloc(/* Heuristic */, size);
    else
        return nodeAlloc(this, size);
}
```

Example: Locality-aware Memory Allocation

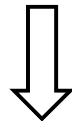
```
void *ptr = ms_getMemory(obs_memorySource(), size);
```



```
void *ptr = ms_getMemory(ms_newMux(), size);
```



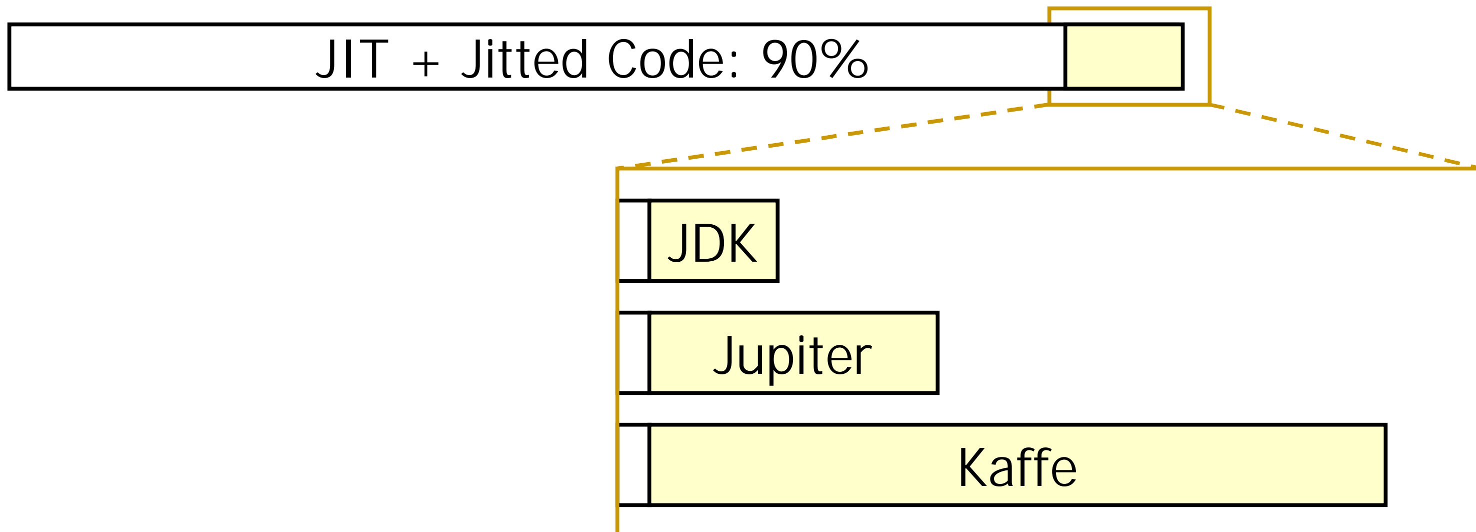
```
void *ptr = ms_getMemory(-1, size);
```



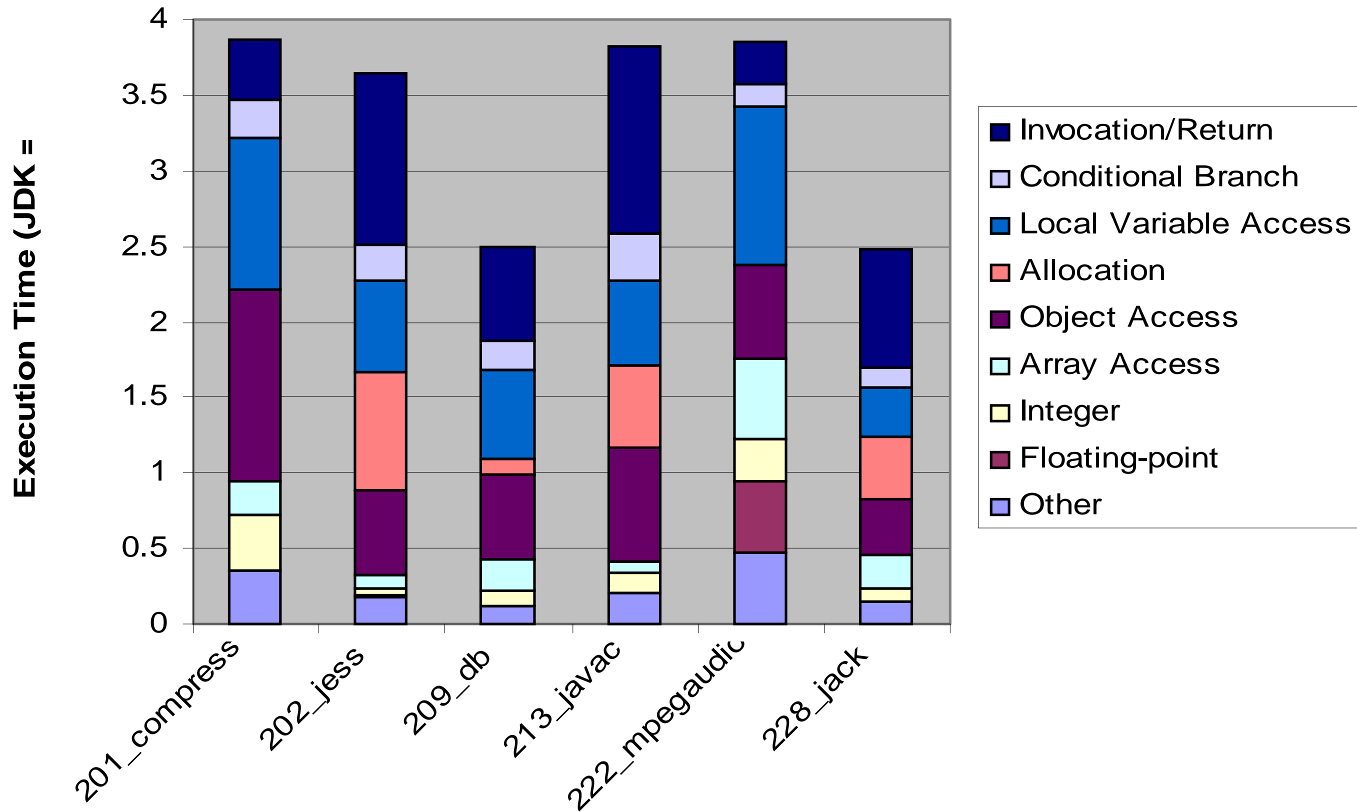
```
void *ptr = nodeAlloc(/* Heuristic */, size);
```

Performance Evaluation

- Single-threaded SPECjvm98 benchmarks.
- Jupiter's interpreter is competitive with other interpreters:
  - 2.65 times faster than Kaffe.
  - 2.20 times slower than Sun's JDK.
- Once a JIT compiler is added, interpreter performance is less significant.
  - Typical results: less than 10% of time spent in interpreter.

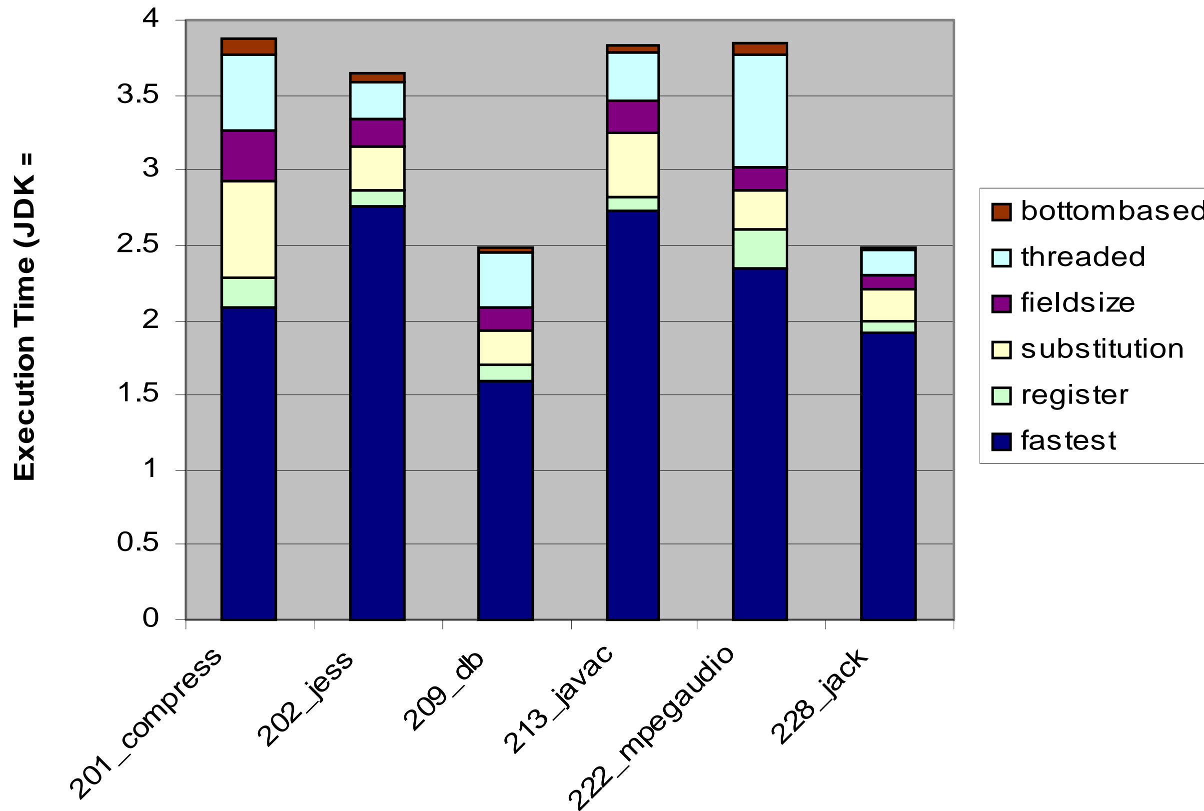


Profile Before Optimizations



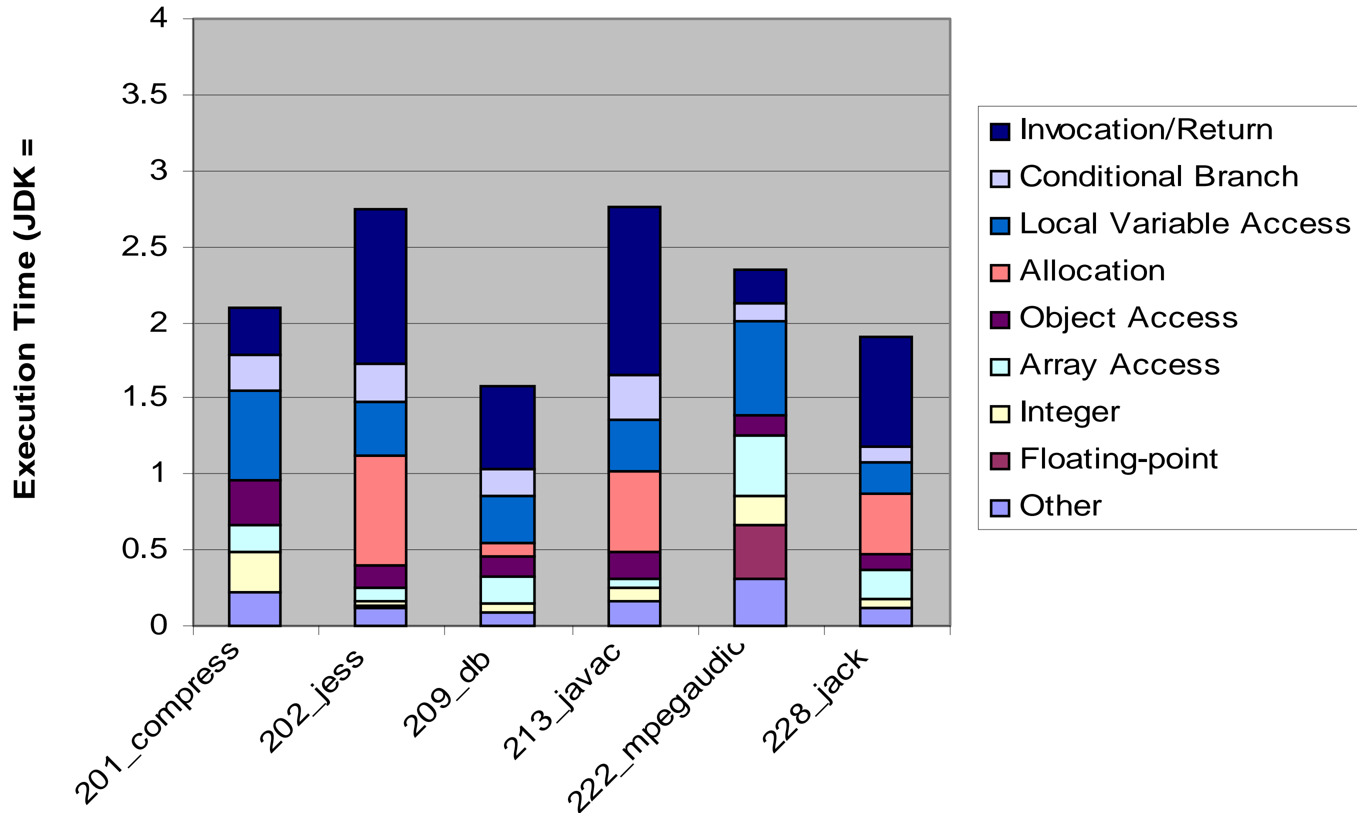
- Opportunities for optimization exist.
  - Object Access: *slow!*

Impact of Successive Optimizations



- Jupiter's flexibility facilitated modifications.
  - Minimal effort.
  - Independent.

Profile After Optimizations



- Object access time greatly improved.
- Opportunities for optimization remain.

Multithreaded Performance

4-Threads/4-Processors

	Benchmark	JDK	Jupiter	Kaffe	Jupiter/JDK	Kaffe/Jupiter
1	205 raytrace	51s	140s	640s	2.72:1	4.58:1
2	Series	103s	127s	313s	1.23:1	2.47:1
3	LUFact	26s	50s	66s	1.95:1	1.30:1
4	Crypt	29s	53s	118s	1.82:1	2.23:1
5	SOR	123s	234s	289s	1.90:1	1.23:1
6	SparseMatmult	46s	85s	294s	1.83:1	3.47:1
7	MolDyn	296s	657s	1578s	2.22:1	2.40:1
8	MonteCarlo	105s	223s	565s	2.21:1	2.43:1
9	RayTracer	373s	886s	3233s	2.37:1	3.65:1
				Geometric Mean	**1.99:1**	**2.43:1**

Conclusions

- Presented a flexible JVM framework.
  - Object-oriented building-block architecture.
  - Carefully-designed module interfaces.

- Competitive early performance.
  - 2.65 times faster than Kaffe.
  - 2.20 times slower than Sun's JDK.

- Suitable for research on JVM scalability and performance issues.

Future Work

- Further interpreter optimizations.
- JIT compiler.
- Parallel scalability and performance research.
- Internet resources:
  - Project Home Page:
    - http://www.eecg.toronto.edu/jupiter
    - Source code download.
  - Patrick Doyle's Jupiter page:
    - http://www.eecg.toronto.edu/~doylep/jupiter
    - Publications.