Starting with Semantics

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How does a computer work?

- How does a CPU work? µop decoding? Pipelining? Speculative execution? Branch prediction? Register renaming?
- How does memory work? Cache coherency? Prefetching? Virtual to physical address translation? Content-addressable memory?
- How does I/O work? PCIe? Programmed I/O? Direct memory access?

It’s a trick question

- Those details are specific to a particular type of computer
- CPU details like this are called microarchitecture, as opposed to the interface visible to the programmer, which is the architecture
- Both systems programmers and compilers for systems languages need to understand the architectural and microarchitectural details
- But what does the systems language itself understand? What machine does the language (as opposed to the compiled code) interact with?

Abstract machines

- An abstract machine is a theoretical model of a computer, expressed as step-by-step execution with architectural details omitted
- Abstract machines may be simplified or detailed, and may be implicit or explicit
- A Turing machine is a simple, explicit abstract machine
- The CLR and JVM are detailed, explicit abstract machines – one way to think about process virtual machines is as executable abstract machines
- C operates over a detailed, implicit abstract machine

Languages and abstract machines

- A programming language describes the steps to take on an abstract machine
- This is true even for non-imperative languages
- Example: the Warren Abstract Machine (WAM) for Prolog
- Example: SECD (stack-environment-control-dump) for strict functional languages

Semantics describe the interface

- There are many ways to describe how a programming language specifies the steps to take on an abstract machine
- The most popular is to write an interpreter or compiler with no specification
- Other approaches include axiomatic semantics, denotational semantics, and operational semantics
- We’ll use operational semantics, but for no reason other than personal preference

Operational semantics

- Big-step operational semantics is a divide-and-conquer approach to calculating the final result of a program – doesn't handle concurrency
- Small-step operational semantics describes a set of transitions, each expressed as an inference rule, that can be applied non-deterministically
- We'll use small-step operational semantics, but each has their purpose

Starting with syntax

- Many programming language designs start with syntax
- In some cases, this is because there is no attempt to intentionally design a semantics – perhaps the semantics was assumed
  - C, Perl, Python, Ruby, R, et al
- In some cases, this is because there is an existing semantics that is intentionally targeted
  - C++, F#, Scala, TypeScript, et al
- These are important and useful approaches!

Starting with the syntax makes sense

- Languages are user interfaces
- Allows the designer to focus on expressiveness, change the paradigm (e.g. functional-first on an existing abstract machine), address software engineering issues (modularity, reuse, etc.), and so much more

Why start with semantics?

- New hardware, e.g. shader languages on GPUs, targeting FPGAs
- New communications mechanisms, e.g. distributed programming languages, distributed transaction processing
- New runtime feature, e.g. garbage collection, hot code loading
- New deployment requirements, e.g. cross-platform, embedded devices
- New application domains, e.g. machine learning, reproducible science
- Evolving concrete machine, e.g. non-uniform memory access, non-volatile memory

Why start with semantics? Part 2!

- Safe languages are designed to mitigate specific security flaws
- Mitigations for languages not designed for them are sometimes possible, and sometimes not cripplingly expensive
- Another route is to design a safe semantics, where safe is always relative to some threat model
- Any language executing with that semantics is then safe, until we figure out what we left out of the threat model

Starting with semantics is harder

- You need to define the abstract machine
- Then you need to define the semantics (interface of language to abstract machine)
- You will still need a syntax
- That syntax will need to target a new and untested semantics
- We can talk about strategies to cope with this later

Let’s build a semantics

- If this is stuff you already know and you want to go faster, please say so
- If this is stuff you don’t feel well grounded in and you want to go slower, please say so
- If you have ideas for how to express things differently, or about something else you’d like to express, please say so

A-normal form

- The operational semantics doesn’t have to be a syntax-driven interpreter
- It can be an intermediate representation between the language and the abstract machine
- Some helpful IR elements are things like single static assignment (SSA), expression holes, continuation passing style (CPS), and A-normal form (ANF)
- We’ll use ANF: we let-bind non-trivial expressions – that is, we use a lot of local variables

$$
\begin{aligned}
x, y, z &\in LocalID \\
\varphi &\in Frame &&= LocalID \to Value \\
v &\in Value &&= Integer
\end{aligned}
$$

$$\frac{\textit{If this holds...}}{\textit{...we are allowed to do this}}$$

$$\frac{}{Frame, Expression \rightsquigarrow Frame, Expression | Value}$$

$$\frac{}{\varphi, e \rightsquigarrow \varphi', e | v}$$

$$\frac{x \in dom(\varphi)}{\varphi, x \rightsquigarrow \varphi, \varphi(x)}$$

$$\frac{}{\varphi, x = v \rightsquigarrow \varphi[x \mapsto v], v}$$

$$\frac{y \in dom(\varphi) \qquad v = \varphi(y)}{\varphi, x = y \rightsquigarrow \varphi[x \mapsto v], v}$$

$$\frac{\begin{array}{c} x \in dom(\varphi) \\ y \in dom(\varphi) \\ v = \varphi(x) + \varphi(y) \end{array}}{\varphi, z = x + y \rightsquigarrow \varphi[z \mapsto v], v}$$

$$\frac{\varphi, e_1 \rightsquigarrow \varphi', e_3}{\varphi, e_1; e_2 \rightsquigarrow \varphi', e_3; e_2}$$

$$\frac{\varphi, e_1 \rightsquigarrow \varphi', v}{\varphi, e_1; e_2 \rightsquigarrow \varphi', e_2}$$

$$\frac{x \in dom(\varphi) \qquad \varphi(x) \neq 0}{\varphi, if(x)\{e_1\}else\{e_2\} \rightsquigarrow \varphi, e_1}$$

$$\frac{x \in dom(\varphi) \qquad \varphi(x) = 0}{\varphi, if(x)\{e_1\}else\{e_2\} \rightsquigarrow \varphi, e_2}$$

$$\frac{}{\varphi, if(*)\{e_1\}else\{e_2\} \rightsquigarrow \varphi, e_1}$$

$$\frac{}{\varphi, if(*)\{e_1\}else\{e_2\} \rightsquigarrow \varphi, e_2}$$

$$\frac{\begin{array}{c} x \in dom(\varphi) \\ \varphi(x) \neq 0 \end{array}}{\varphi, while(x)\{e\} \rightsquigarrow \varphi, e; while(x)\{e\}}$$

$$\frac{x \in dom(\varphi) \qquad \varphi(x) = 0}{\varphi, while(x)\{e\} \rightsquigarrow \varphi, 0}$$

A simple sequential semantics

- We can extend this with function calls, turning the frame into a stack of frames
- And add a heap, and allocation on the heap
- We can add manual free, or reference counting, or a non-deterministic garbage collector
- We can extend values to include addresses on the heap
- And add structured data with fields
- And extend that structured data with methods, dynamic dispatch, and dynamic type information (objects)

More complex sequential semantics?

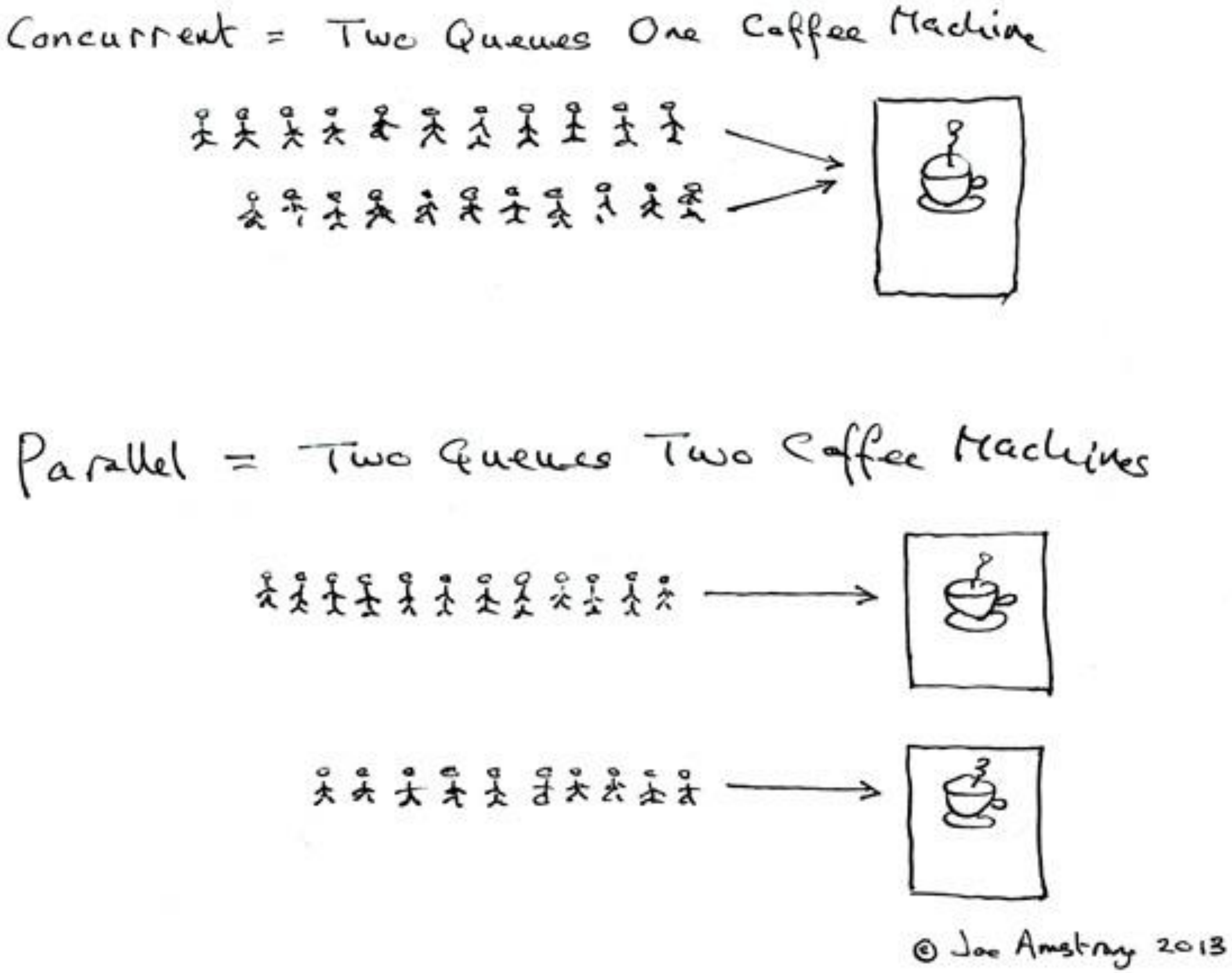
- Tail call optimisation is just that – an implementation optimisation over the stack semantics
- Pattern matching, higher order functions, and call-by-need (lazy evaluation) can be expressed in terms of the simple sequential semantics
- So can multiple-dispatch, logic programming, exception handling, and more

System level sequential semantics

- Vectorisation (SIMD) and non-strict floating-point maths are relatively straight-forward extensions
- Interrupt handling and dynamic linkage are tricky, and system specific, such that finding the right abstract machine representation is hard
- Interrupt handling is not parallel, but it is asynchronous

A parallel semantics

- The standard abstract machine is a parallel random-access machine (PRAM)
- Add multiple stacks (i.e. threads) and non-deterministically select which stack to execute next
- Keep a single shared heap
- Add a collection of atomic operations, expressed as inference rules that complete the operation in a single small-step
- Small-step operational semantics expresses concurrency by using non-determinism to model parallelism


Concurrent = Two Queues One Coffee Machine
Parallel = Two Queues Two Coffee Machines
© Joe Armstrong 2013

$$
\begin{aligned}
v &\in Value &&= Integer | Address \\
\chi &\in Heap &&= Address \rightarrow Object \\
\sigma &\in Stack &&= \overline{Frame} \\
\theta &\in Thread &&= Stack \times Expression
\end{aligned}
$$

$$\frac{}{\chi, \sigma \cdot \varphi, e \rightsquigarrow \chi', \sigma \cdot \varphi', e|v}$$

$$\frac{\chi, \sigma, e \leadsto \chi', \sigma', e'}{\chi, \overline{\theta} \cdot (\sigma, e) \cdot \overline{\theta'} \leadsto \chi', \overline{\theta} \cdot (\sigma', e') \cdot \overline{\theta'}}$$

$$\frac{\chi, \sigma, e \leadsto \chi', \sigma', v}{\chi, \overline{\theta} \cdot (\sigma, e) \cdot \overline{\theta'} \leadsto \chi', \overline{\theta} \cdot \overline{\theta'}}$$

Memory ordering

- This approach results in a semantics for parallelism that is sequentially consistent – all reads and writes from all threads are locally in-order and globally interleaved in some total order
- There are many forms of more relaxed memory ordering on real CPUs, which are critical for performance – weak memory semantics is an active research area
- Even without relaxed memory orderings, concurrency in the PRAM model allows concurrent mutation (data races)

A use case for starting with semantics

- We can express an operational semantics that has mutation, is parallel, is efficiently implementable, but has no concurrent mutation
- This is an example of the abstract machine allowing less than the concrete machine
- Restricting the abstract machine can improve reasoning, safety, and performance
- The implicit C abstract machine, for example, has a flat, undifferentiated address space – restricting this is an active research area

Why remove concurrent mutation?

- Very roughly speaking, the top safety issues in systems programming languages, in order:
  - Spatial memory safety
  - Temporal memory safety
  - Data races
- If concurrent mutation isn't necessary for your problem domain, removing it can improve safety and performance
- There are many approaches, from transactional memory to linear types – this is just a point in the design space

Building a PRAM without data-races

- In the PRAM model, there is a single shared heap
- We can instead associate a heap with each thread
- This eliminates data-races completely – each thread can only read or write its own heap and its own stack
- It also removes the only cross-thread communication mechanism, which was observing concurrent mutation in the heap

Adding data-race free communication

- We can associate a mailbox with each thread
- The mailbox can allow concurrent push but only allow the associated thread to pop – a multi-producer single-consumer (MPSC) queue
- If mailbox messages must be primitive values, we have data-race free communication
- But we want safe, efficient communication of structured data, including entire object graphs

Object messaging without data-races

- We could prevent the receiving thread from making progress and copy the message graph into the receiving heap – slow but effective (Erlang)
- We can ensure that the message graph does not reach any object reachable by the sending thread
- This is a form of separation logic – safe and fast messaging, but only if the reachability test is cheap

Simple separation logic encoded in semantics

- Use a single heap, segmented into regions, where every object belongs to one region and is reachable only from that region
- Allow objects in some region r to reference some other region r’ but not the objects within r’
- Reference count regions
- Messages may then contain only regions with a zero reference count, and never object references
- This allows moving a region from one thread to another but not sharing a region, preventing concurrent mutation

Weakening the semantics

- This simple encoding of separation logic can be drastically improved, including by moving some elements from the dynamic domain (operational semantics) to the static (type checking)
- This can be allowed in the operational semantics by not specifying the way separation is enforced
- Instead, inference rules can have complex preconditions that may be enforced statically rather than dynamically

Another use case: memory constrained ML

- The other ML: machine learning
- Specifying vector operations needed for efficient ML is simple
- Less simple is scheduling parallel pipeline stage executions in a constrained memory environment
- Particularly for ML pipelines that are dynamically data dependent: recursive, looping, etc.

Key takeaways

- Starting with semantics means building a language to do something *different* rather than building a language to do something *better*
- Detailed, explicit small-step operational semantics are surprisingly easy to get right if they are there from the beginning
- A new semantics can free you from problems arising from your abstract machine that are due to features you don’t need for your problem domain