The Reduceron

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Talk given at Birmingham University, April 2009

Observation 1

Efficient compilation of high-level functional programs on conventional computers is a big challenge.

Sophisticated techniques needed to exploit architectural features designed for low-level imperative execution.

"I wonder how popular Haskell needs to become for Intel to optimize their processors for my runtime, rather than the other way around."

Simon Marlow, 2009

Observation 2

The target (architecture) changes!

"In light of evidence that Haskell programs compiled by GHC exhibit large numbers of mispredicted branches on modern processors, we re-examine the tagless aspect of the STG-machine."

Marlow et al., 2007

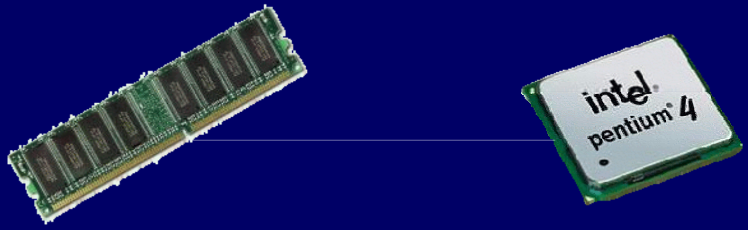
"We also discovered that one optimisation in the STG-machine, vectored-returns, is no longer worthwhile."

Marlow et al., 2007

Observation 3

Conventional computers have inherent limitations when it comes to running functional programs.

Memory Bottleneck



“Much of the implicit parallelism available in Haskell programs is at too fine a granularity for it to be exploitable on stock hardware.”

Harris, 2008

Question

Why not build a machine especially
to run functional programs?

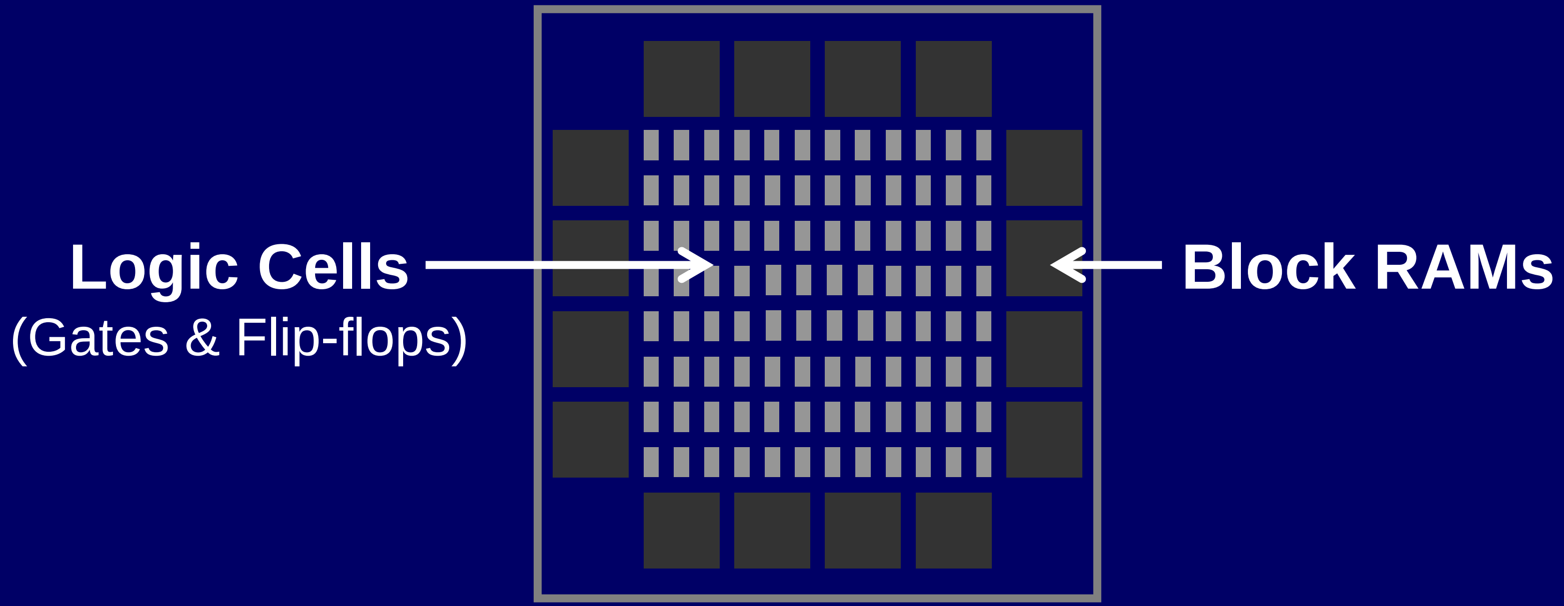
"Current RISC technology will probably have increased in speed enough by the time a graph-reduction chip could be designed and fabricated to make the exercise pointless."

Koopman, 1990

But now the situation is changing…

FPGAs (think Lego)

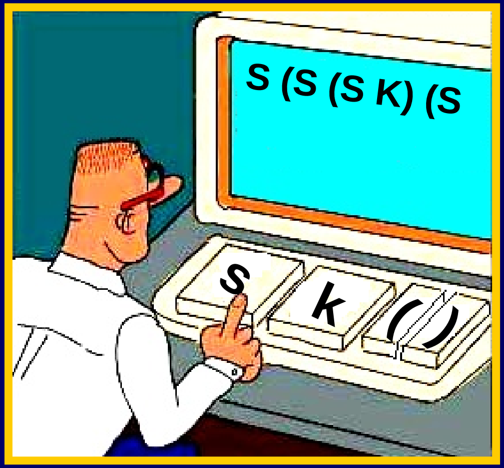
Contain a large, fixed set of components that can be connected together in any desired way.



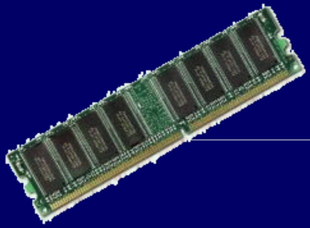
Widely available, and quick to program.

The Reduceron

A computer designed to run lazy functional programs,



not restricted by conventional architectural constraints,



implemented on an FPGA, using a functional language.

Project status

- Initially developed as *part* of my PhD
  - submitted September 2008.
- Now a 15-month EPSRC project
  - started October 2008;
  - one Professor, one RA, one under-graduate.
- Broad aim: fast reduction!
  - Explore what is possible, in a few directions.

Lazy evaluation

Quick recap

Reduction strategies

Suppose that **`double`** is defined by

```
double x   =   x + x
```

and we wish to reduce

```
double (1 + 1)
```

then there are **two** main strategies.

1. Innermost

Suppose that **`double`** is defined by

```
double x   =   x + x
```

then, using the **innermost strategy**,

```
      double (1 + 1)
=>    double 2
=>    2 + 2
=>    4
```

2. Outermost

Suppose that **`double`** is defined by

```
double x   =   x + x
```

then, using the **outermost strategy**,

```
      double (1 + 1)
=>    (1 + 1) + (1 + 1)
=>    2 + (1 + 1)
=>    2 + 2
=>    4
```

2. Outermost

Suppose that **`double`** is defined by

```
double x    =    x + x
```

then, using the **outermost strategy**,

```
      double (1 + 1)
=>    (1 + 1) + (1 + 1)
=>    2 + (1 + 1)
=>    2 + 2
=>    4
```

Reduced twice!

Evaluation strategies

How many times is a function argument evaluated?

Innermost:	**Exactly once**
Outermost:	**Zero or more**

Evaluation strategies

How many times is a function argument evaluated?

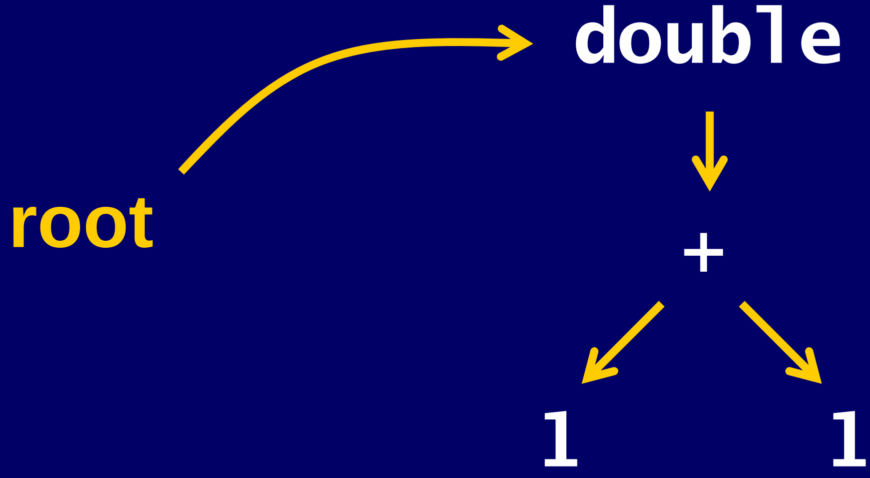
Innermost:	**Exactly once**
Outermost:	**Zero or more**
Lazy:	**Zero or once**

Expressions as graphs

Suppose that **`double`** is defined by

```
double x    =    x + x
```

and we wish to reduce **`double (1 + 1)`**.

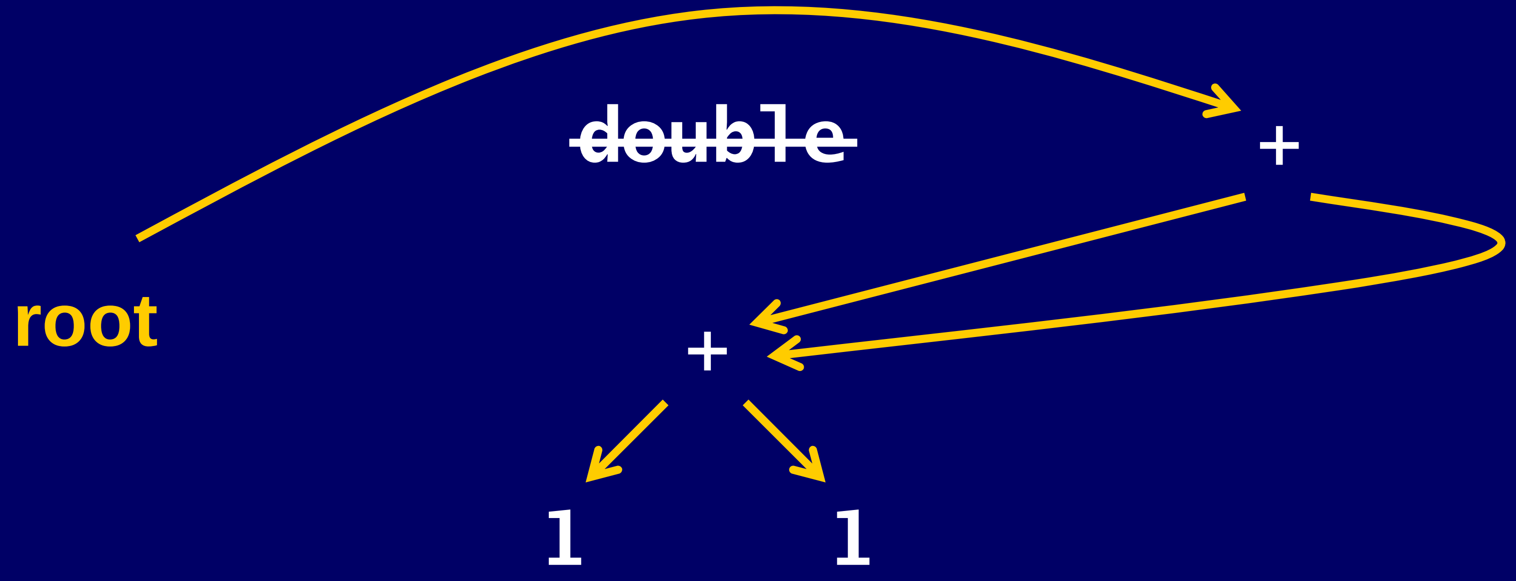


Graph reduction

Suppose that **`double`** is defined by

```
double x   =   x + x
```

then, by **lazy evaluation**,



Graph reduction

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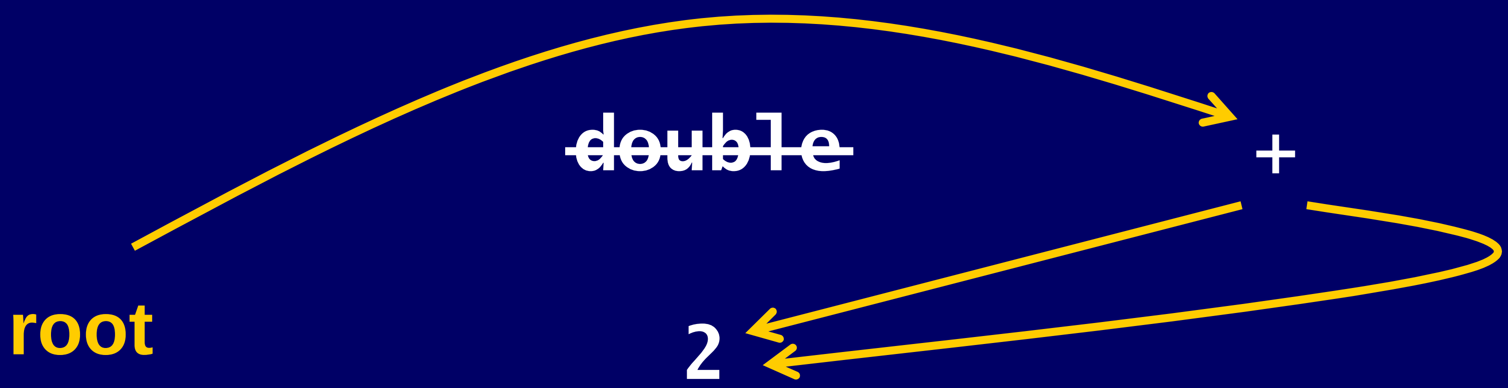


Graph reduction

Suppose that **`double`** is defined by

```
double x    =    x + x
```

then, by **lazy evaluation**,

~~`double`~~ → **4**

root

Graph reduction machines

Widening the von Neumann Bottleneck

Graph reduction machines

Suppose that function **`f`** is defined by

```
f x y z   =   g y (h z x)
```

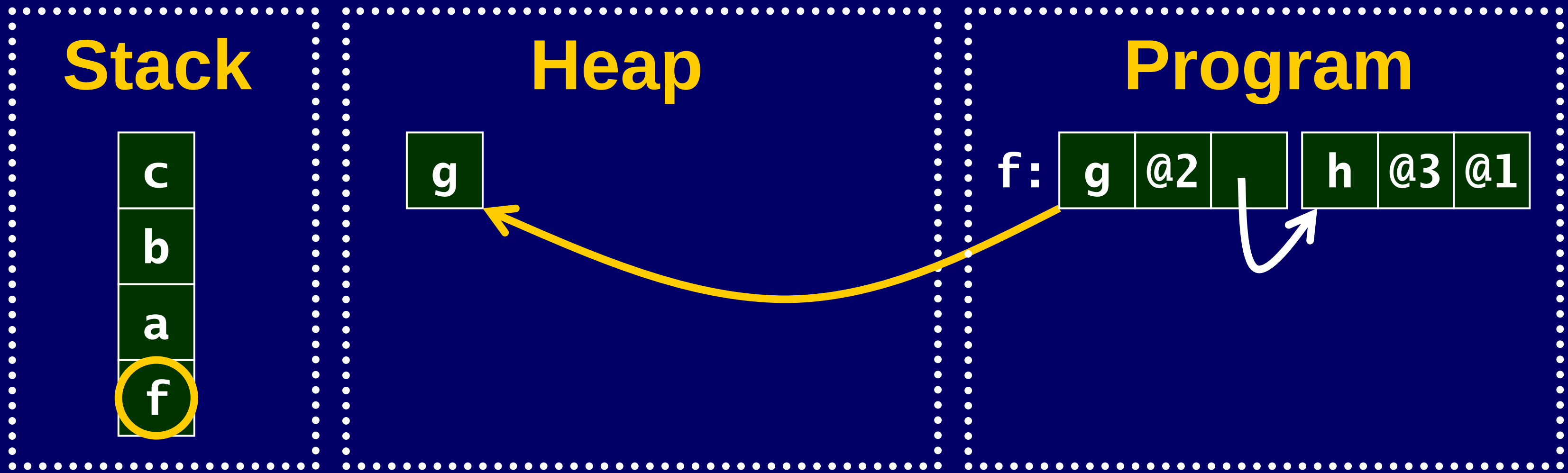
where **g** and **h** are functions and the following machine-state arises during reduction.

Graph reduction machines

Operation:

```
f <- Stack[0]
g <- Code[f]
g -> Heap
```

Count: 3



Graph reduction machines

Operation:

```
arg <- Code[f+1]
b   <- Stack[arg]
b   -> Heap
```

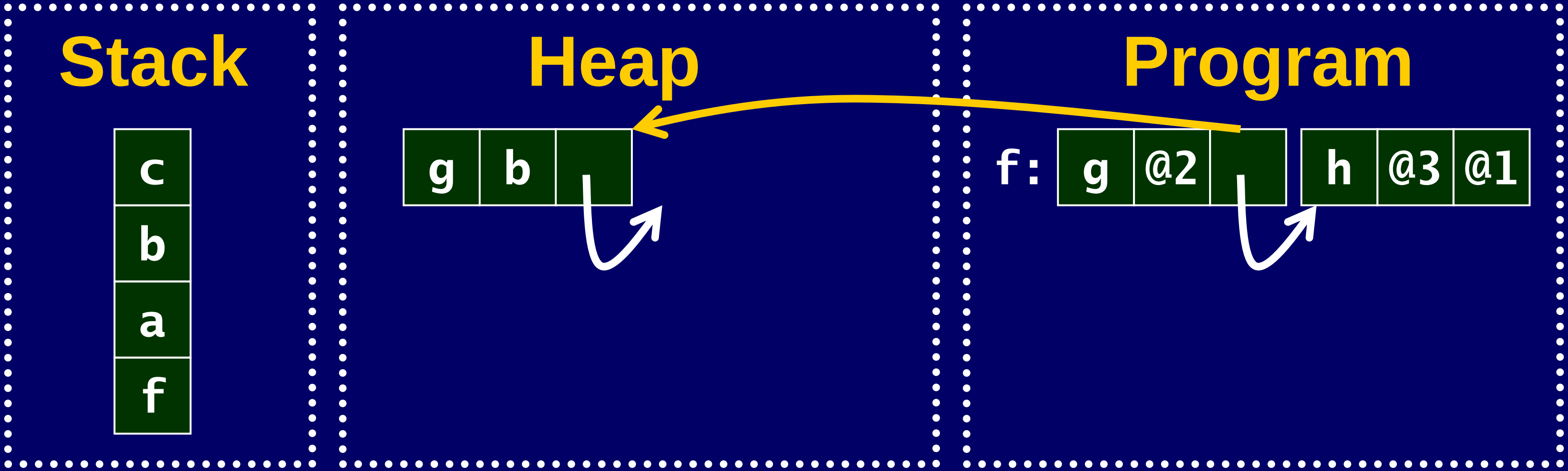
Count: 6

Graph reduction machines

Operation:

```
ptr  <- Code[f+2]
ptr' -> Heap
```

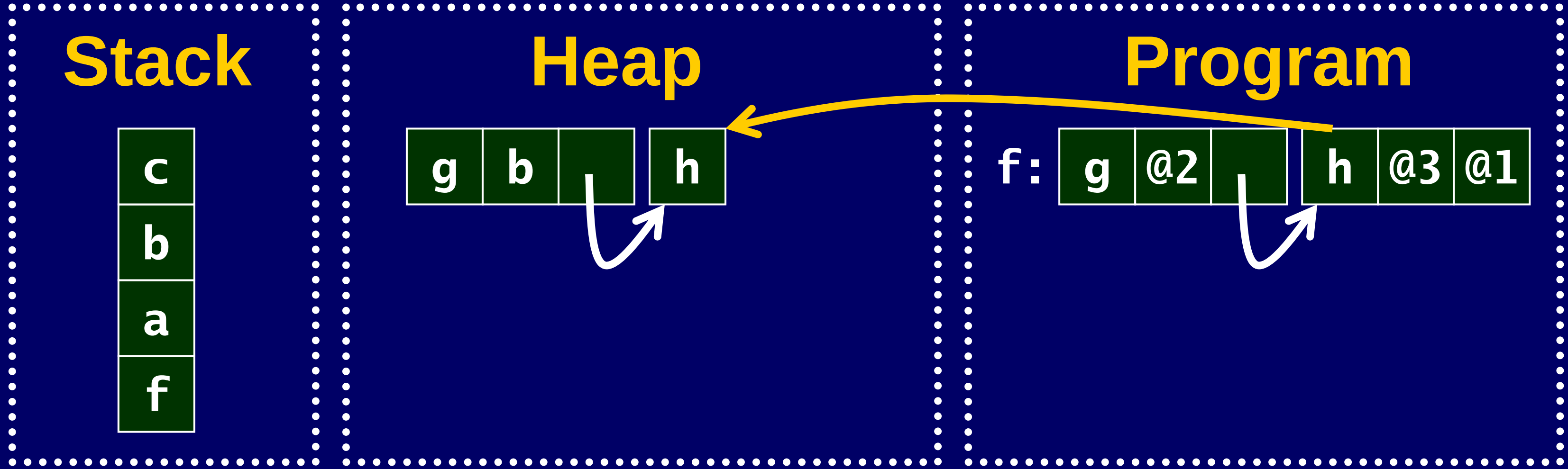
Count: 8



Graph reduction machines

Operation: `h <- Code[f+3]`
`h -> Heap`

Count: 10

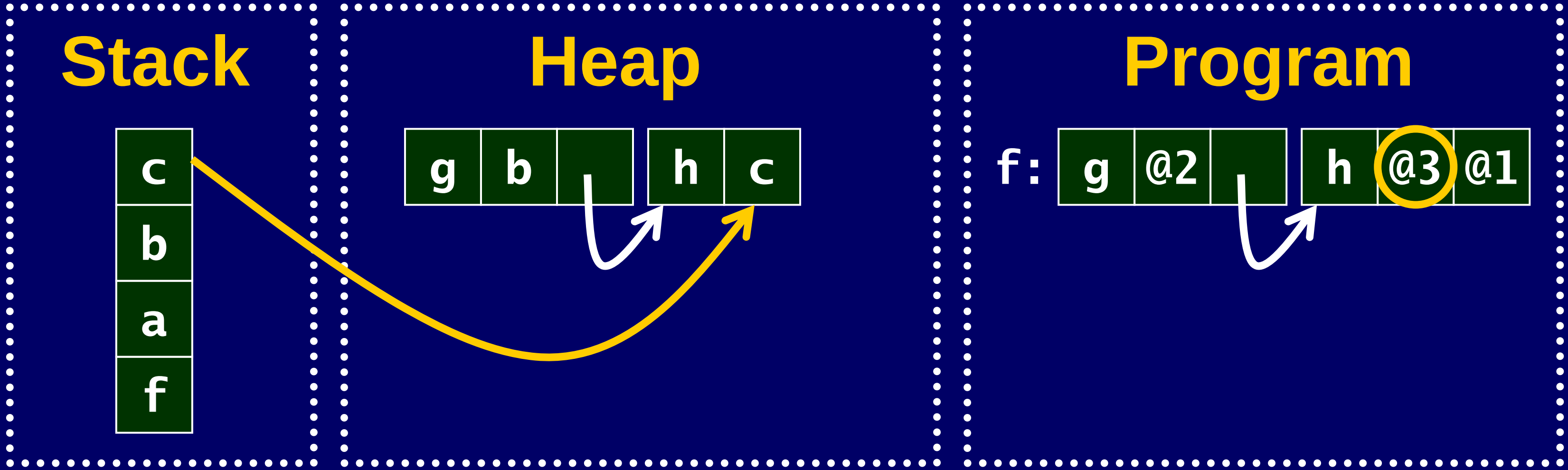


Graph reduction machines

Operation:

```
arg <- Code[f+4]
c   <- Stack[arg]
c   -> Heap
```

Count: 13

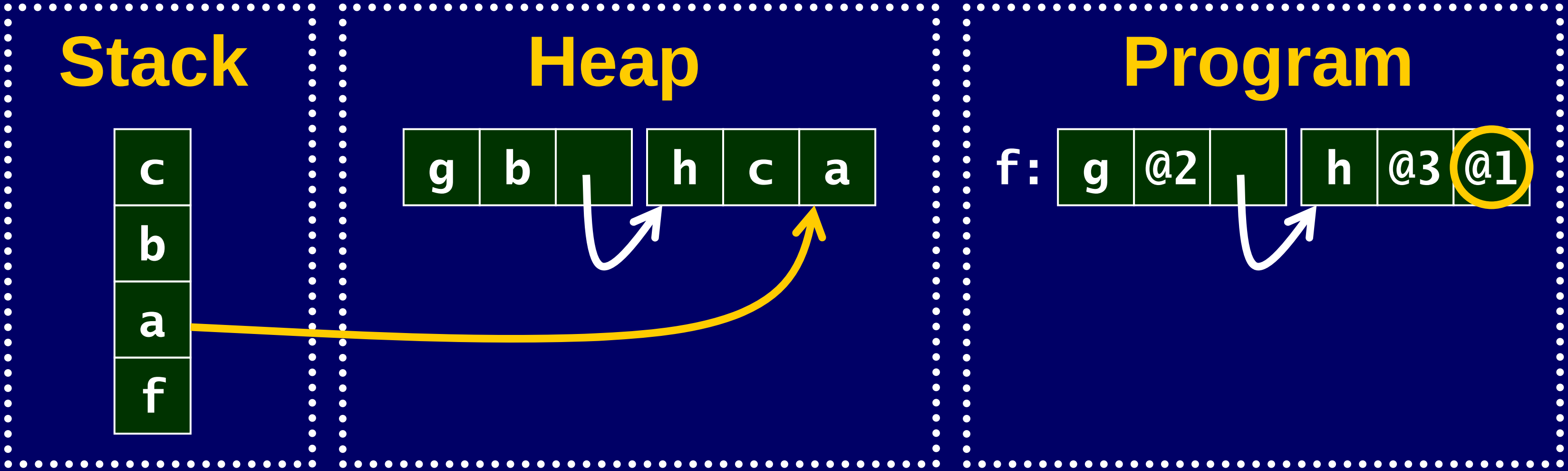


Graph reduction machines

Operation:

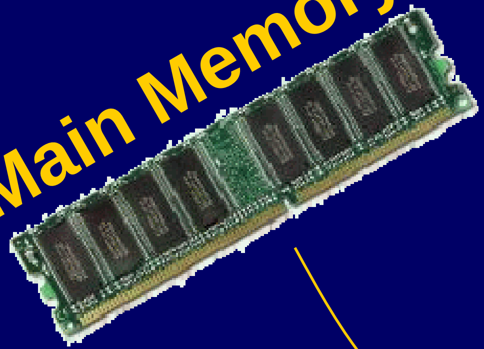
```
arg <- Code[f+5]
a   <- Stack[arg]
a   -> Heap
```

Count: 16



The von Neumann Bottleneck

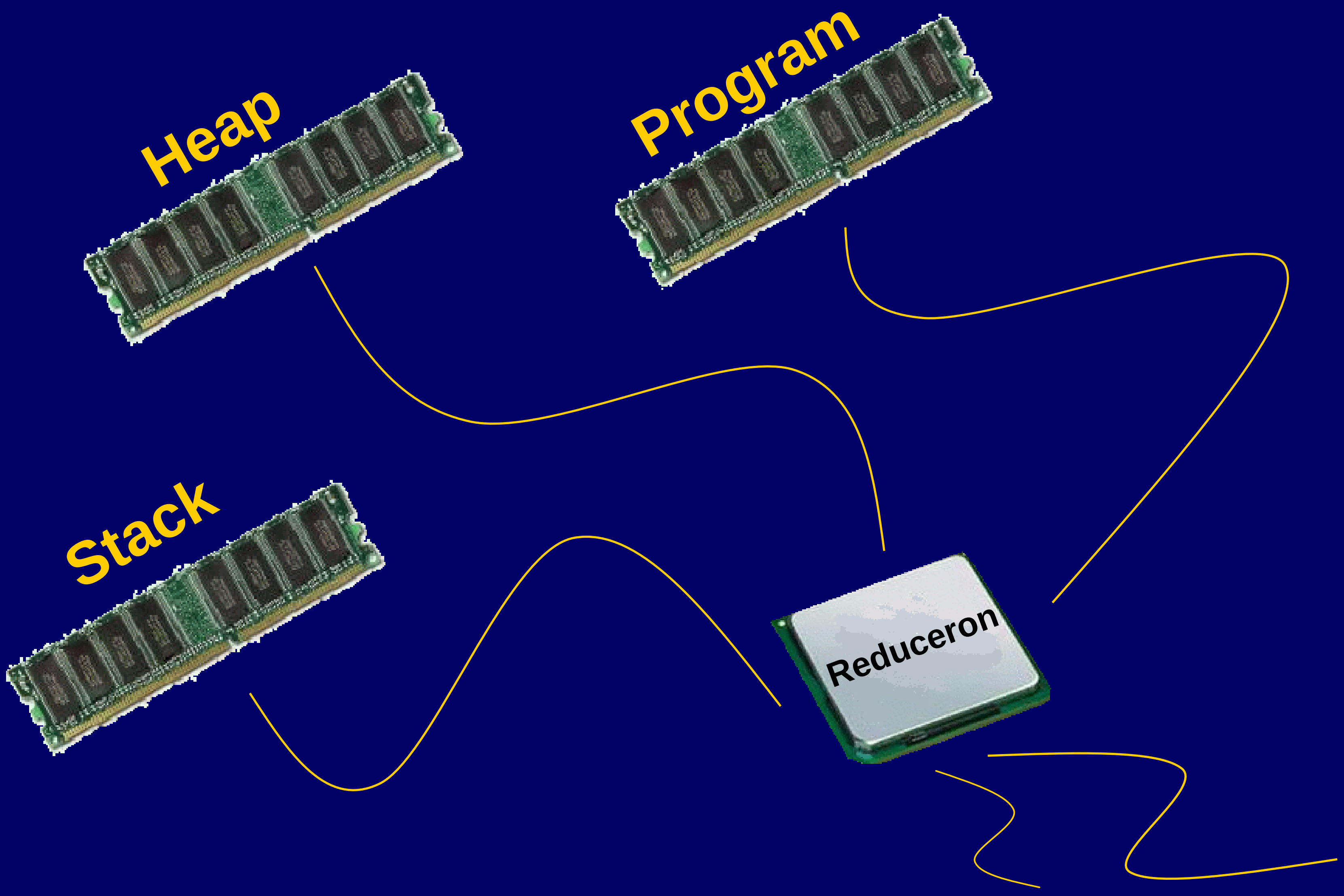
Main Memory



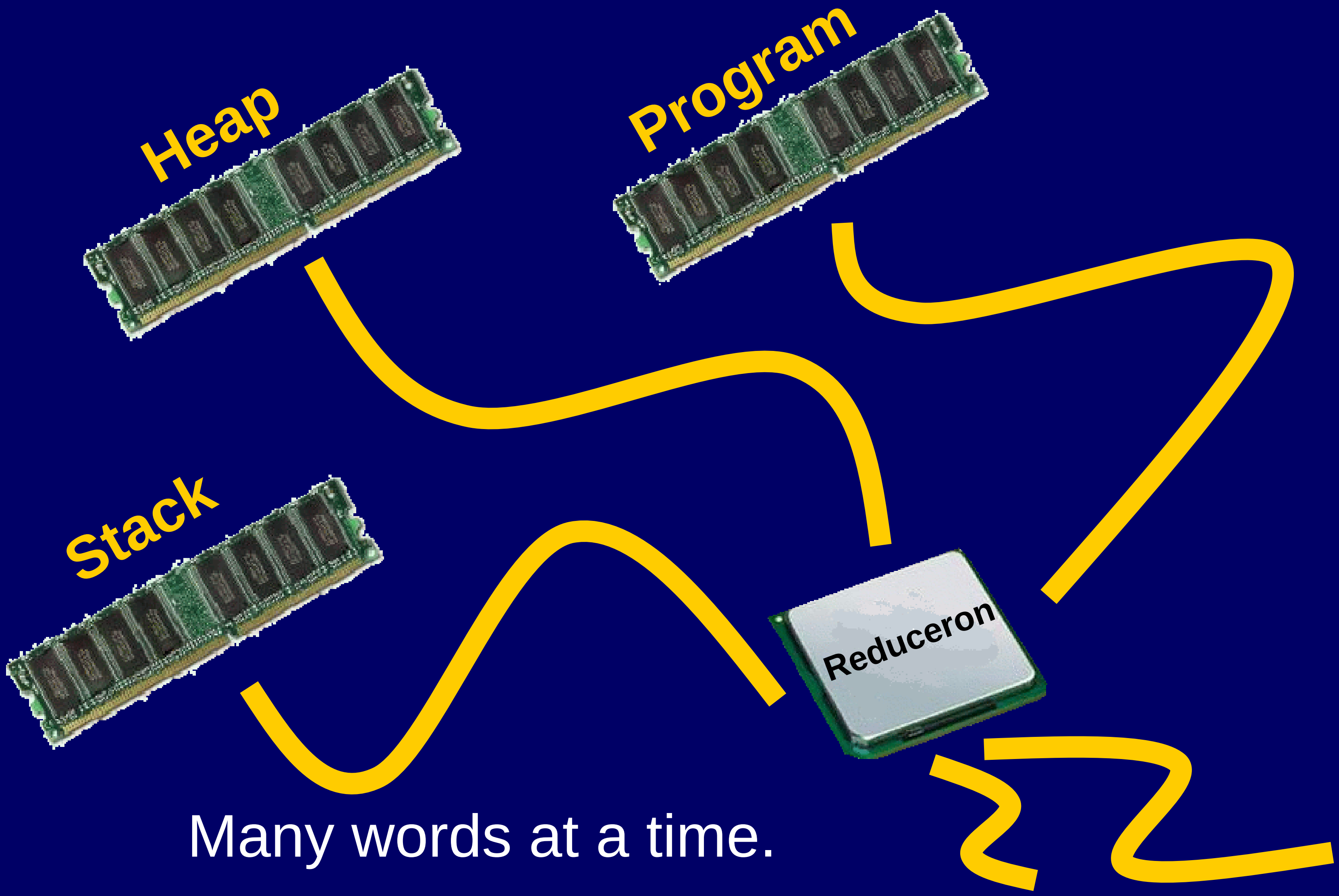
One word at a time.

Each of the **16** memory transactions is done sequentially.

Widening the Bottleneck



Widening the Bottleneck, again



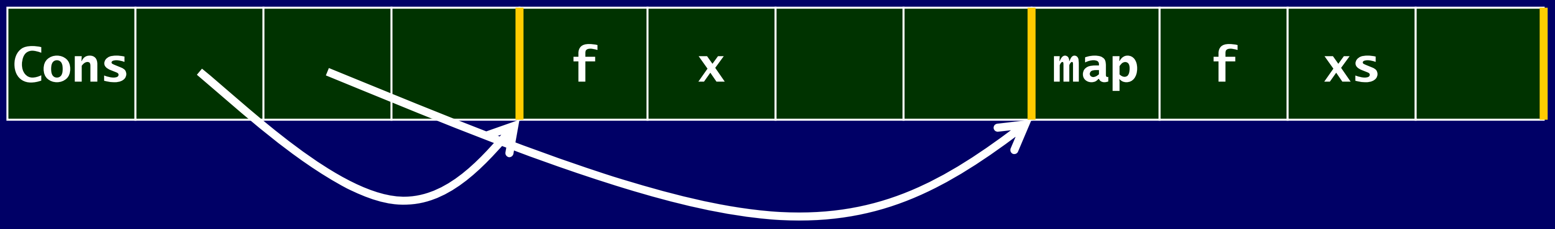
Many words at a time.

Heap layout

The expression

`Cons (f x) (map f xs)`

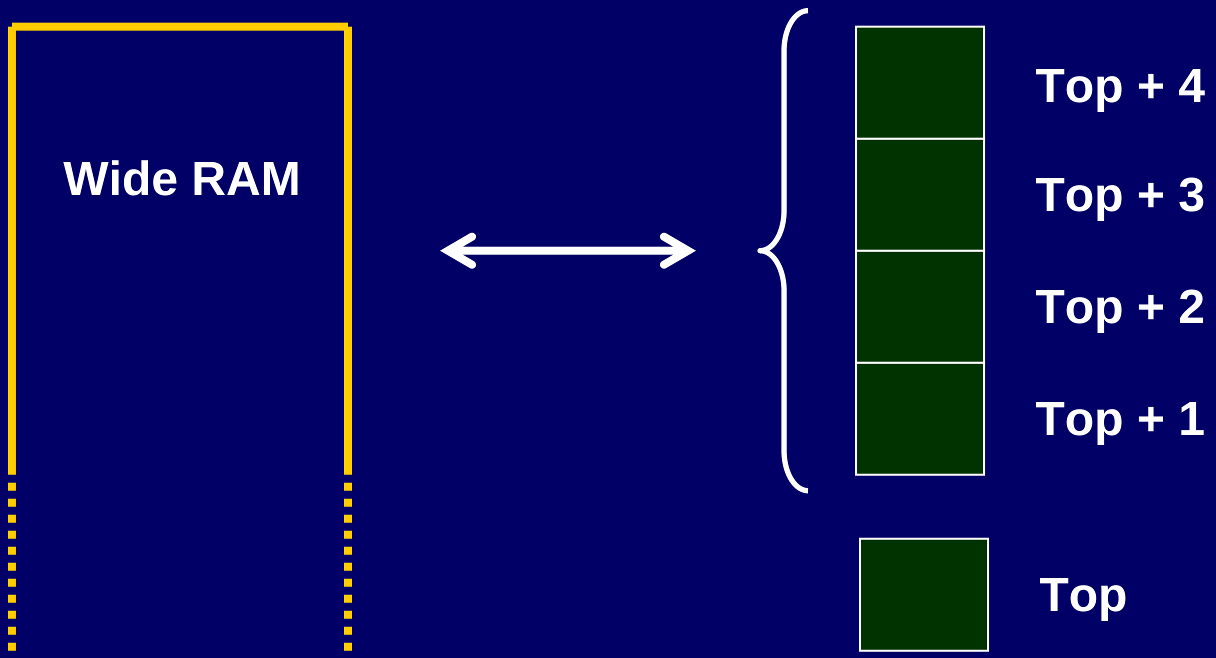
is represented in memory as



Two 4-word applications can be read or written per clock cycle.

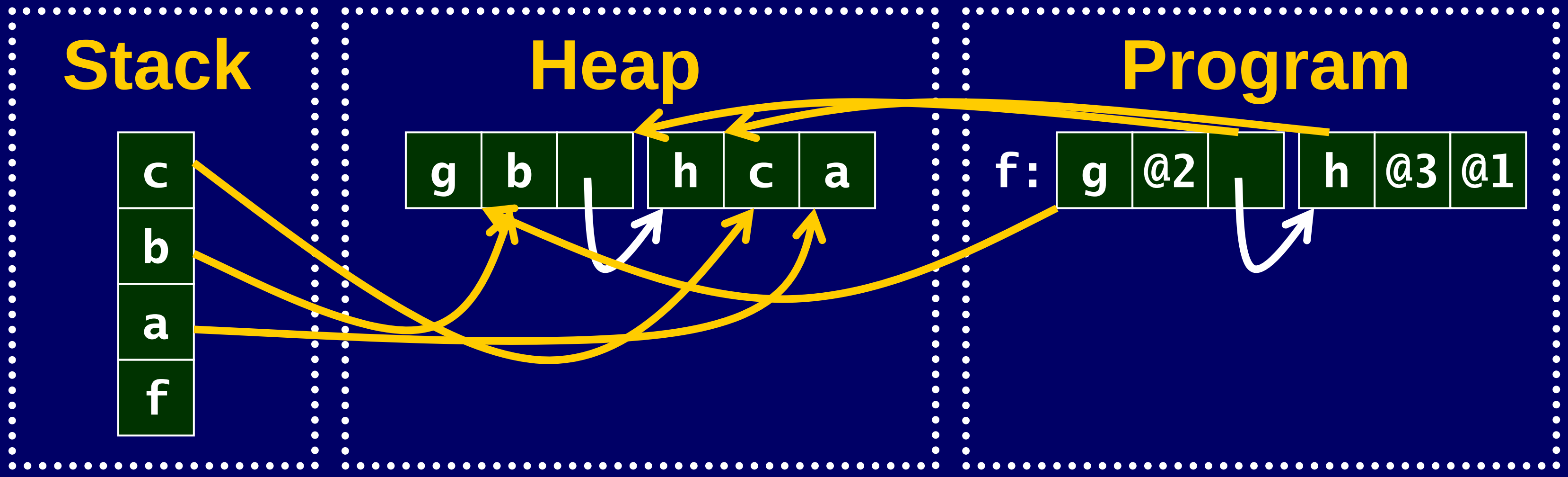
Stack layout

Top elements can be stored in registers.



Up to 5 words can be pushed & popped per cycle.

Applying a function “in one go”



The function `f` can be applied in a single clock cycle.

A note about memory

- For *simplicity* and *flexibility*, we make sole use of FPGA block RAMs, no off-chip memories.

- The total block RAM capacity of the latest Xilinx FPGAs is only *five megabytes*.

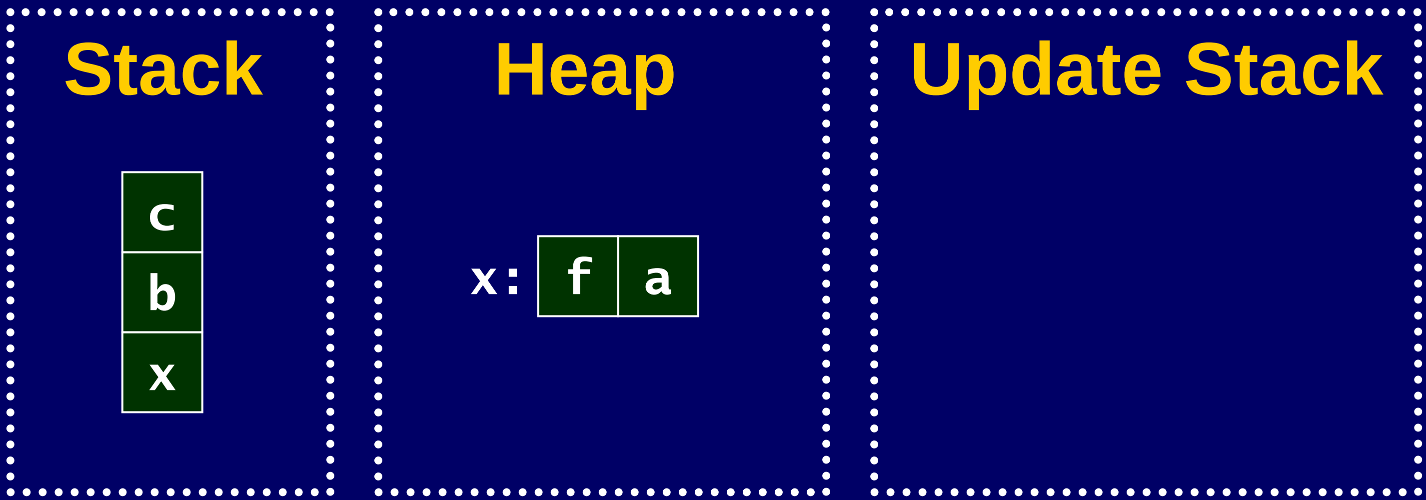
- Some consider this to be a *serious* limitation.
  - But FPGAs continue to get bigger and bigger…

Further widening (1)

The update stack

The update stack

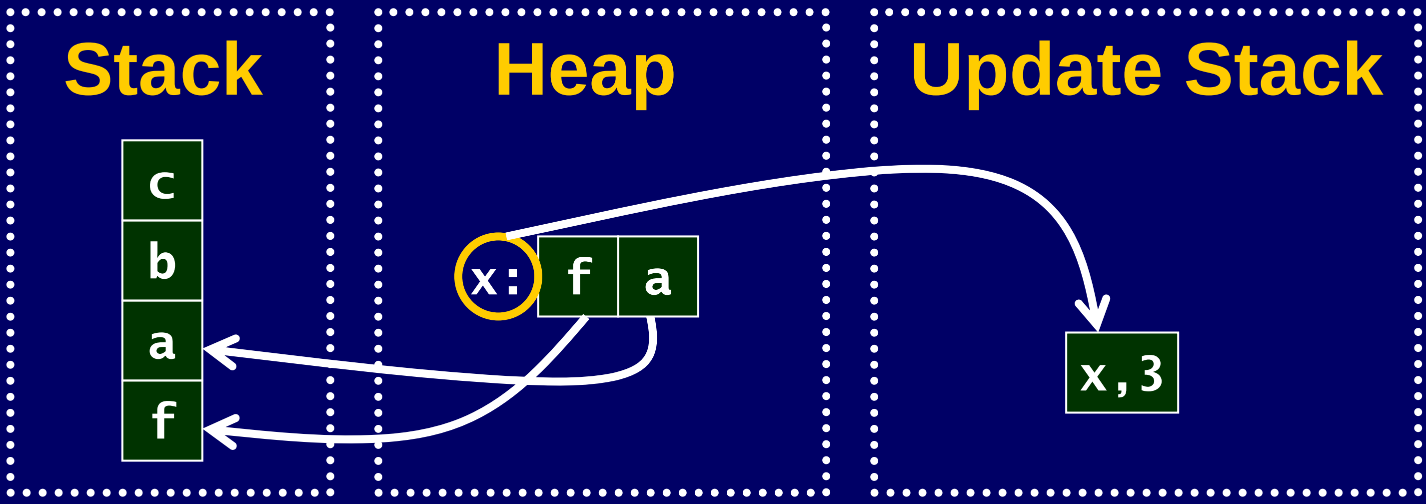
When a pointer to an application **x** on the heap appears on top of the stack,



the application is copied from heap to stack, ***and*** a pointer/stack-size pair is pushed onto the update stack.

The update stack

***Idea**: when evaluation of* **`f a`** *is complete, the value at* **`x`** *can be updated with the result.*



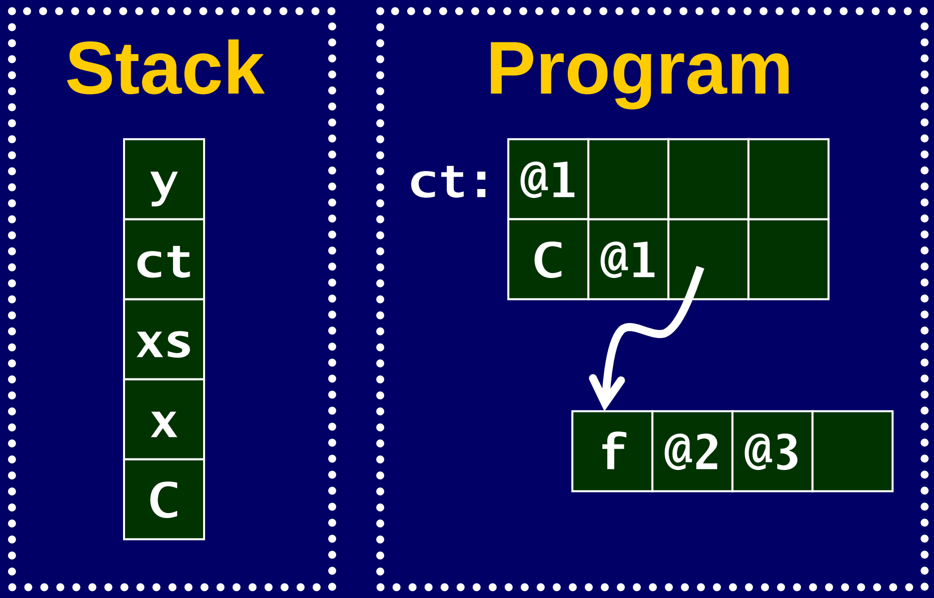
Writing to stack and update-stack is done in parallel.

Further widening (2)

The case stack

The case stack

When a data constructor is on top of the stack,



the corresponding case alternative is chosen from the ***case table***, pointed to by **`ct`**.

The case stack

Problem: pointer to case table must be fetched from the value stack, and it is not always in the same position! This look-up consumes a cycle.

Solution: store case table pointers on a separate stack. The case table pointer of interest is always at the top.

A separate case stack allows zero-cycle matching.

Reduceron “instruction set”

Operation	**Clock cycles**
Apply	$\lceil \mathbf{n}/2 \rceil$
Unwind	1
Update	1
Swap	1
Primitive Apply	1

Where **n** = number of ***applications*** in function body.

Dynamic analysis (1)

Update avoidance

Shared applications

Distinguish between:

- ***unshared*** applications, and
- ***possibly-shared*** applications.

Idea: *When an unshared application is reduced to normal form, no update is needed.*

Dynamic vs. static analysis

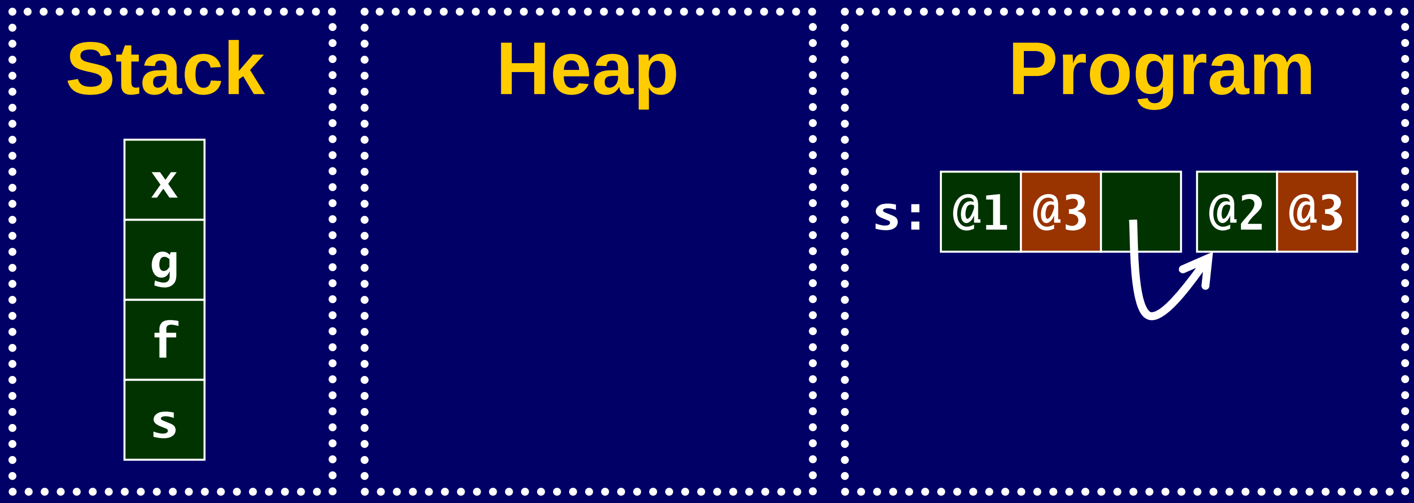
"Create all closures as [unshared], and dynamically change their tag to [possibly-shared] if they become shared. We call this operation ***dashing.****"*

"In general we strongly suspect that the cost of ***dashing*** *greatly outweighs the advantages of precision when compared to the [static analysis] method."*

Peyton Jones, 1988

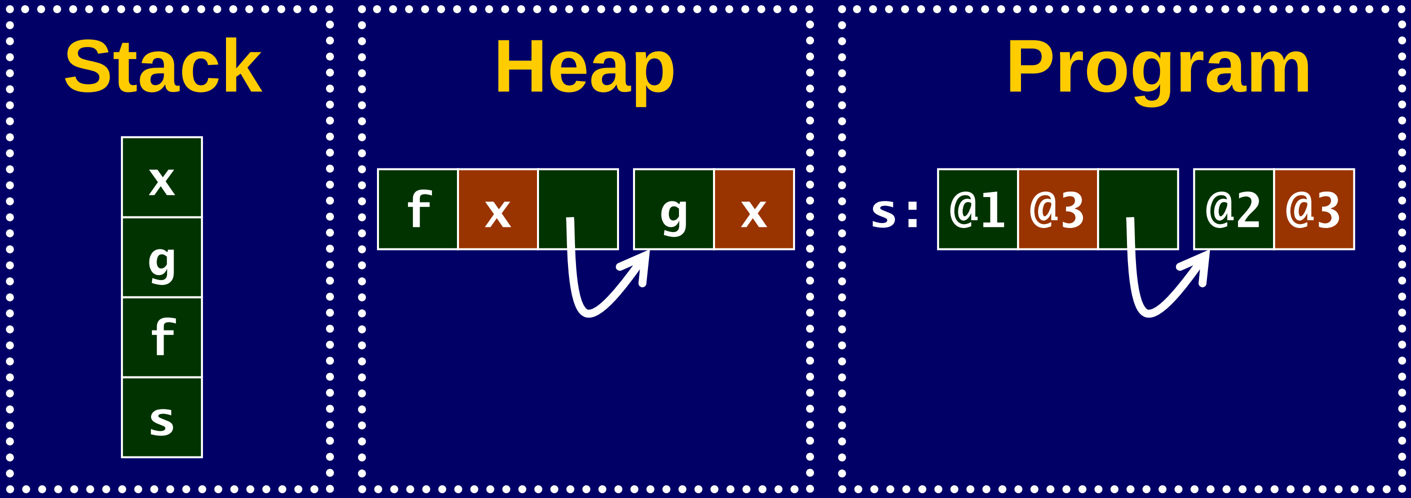
Dashing when applying

When the function ***s***, containing two references to its 3rd parameter, is applied,



Dashing when applying

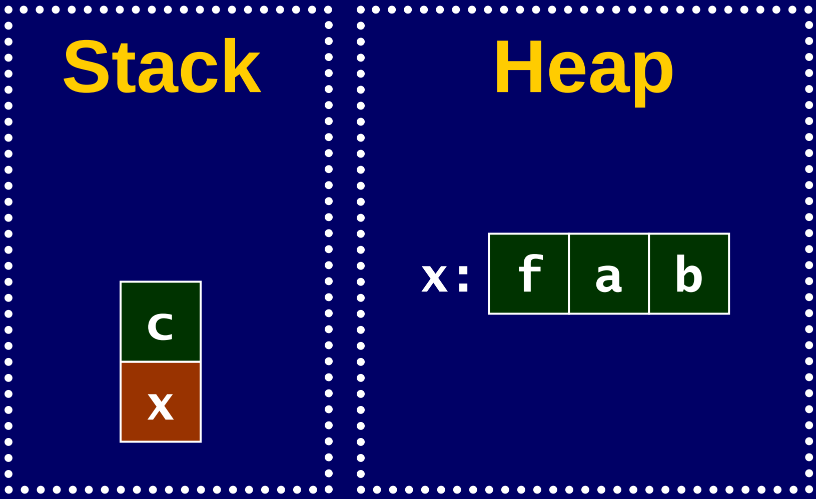
When the function ***s***, containing two references to its 3rd argument, is applied,



the 3rd argument is dashed.

Dashing when unwinding

When a pointer **x** to a shared application appears on top of the stack,



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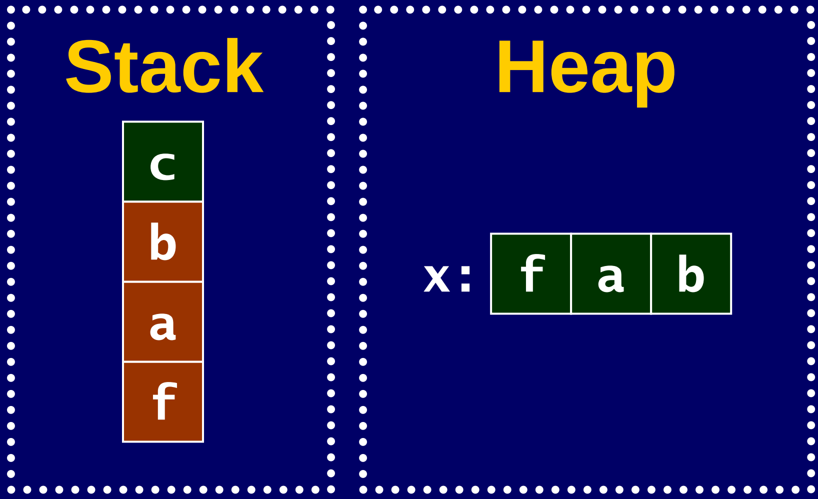
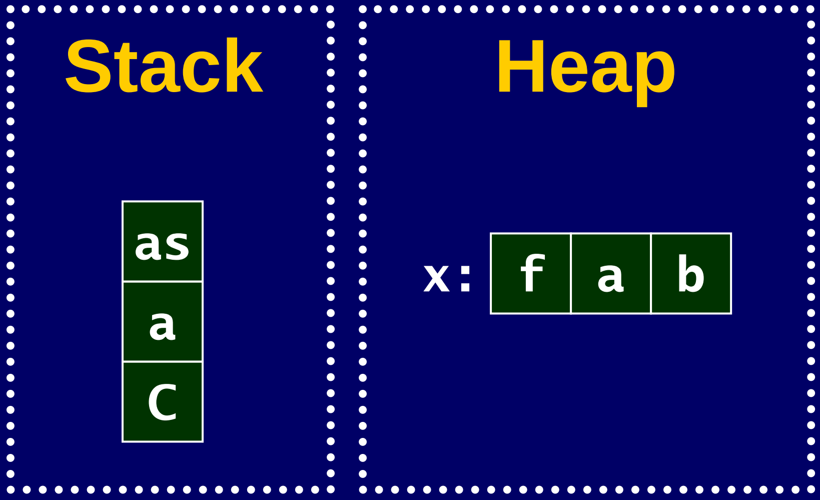


the unwound application is dashed.

Dashing when updating

When a normal-form has been reached,



Dashing when updating

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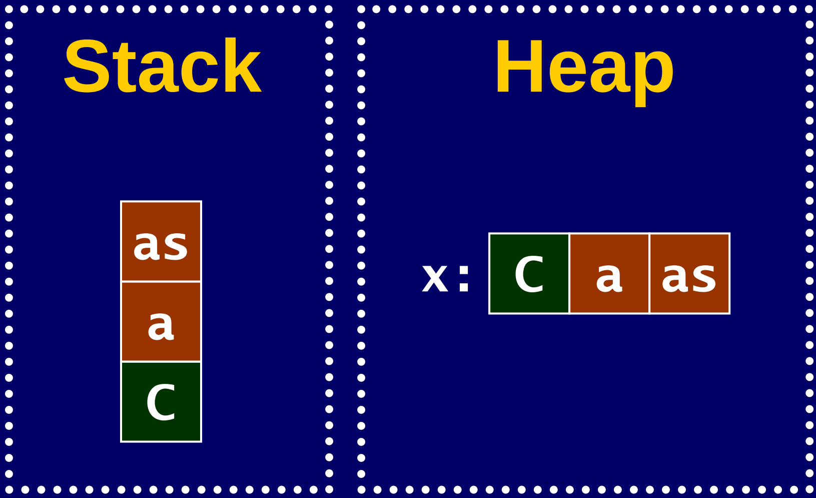


it is copied onto the heap, overwriting the original application, and its arguments are dashed.

Dynamic vs. static analysis

In the Reduceron, dynamic update avoidance is cheap: it’s just bit-flipping under some simple-to-compute conditions.

Dynamic analysis (2)

Speculative evaluation of primitive redexes

(Not implemented yet!)

Primitive redexes

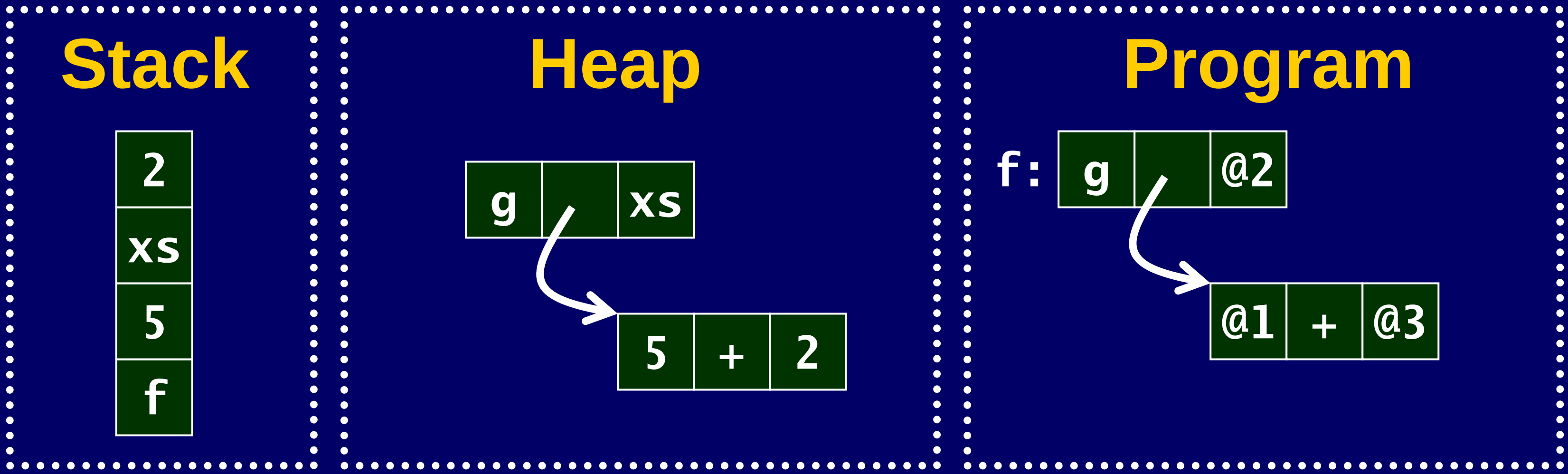
Suppose that function **`f`** is defined by

```
f x xs a   =   g (x+a) xs
```

where **`g`** is a function, and **`+`** is primitive addition.

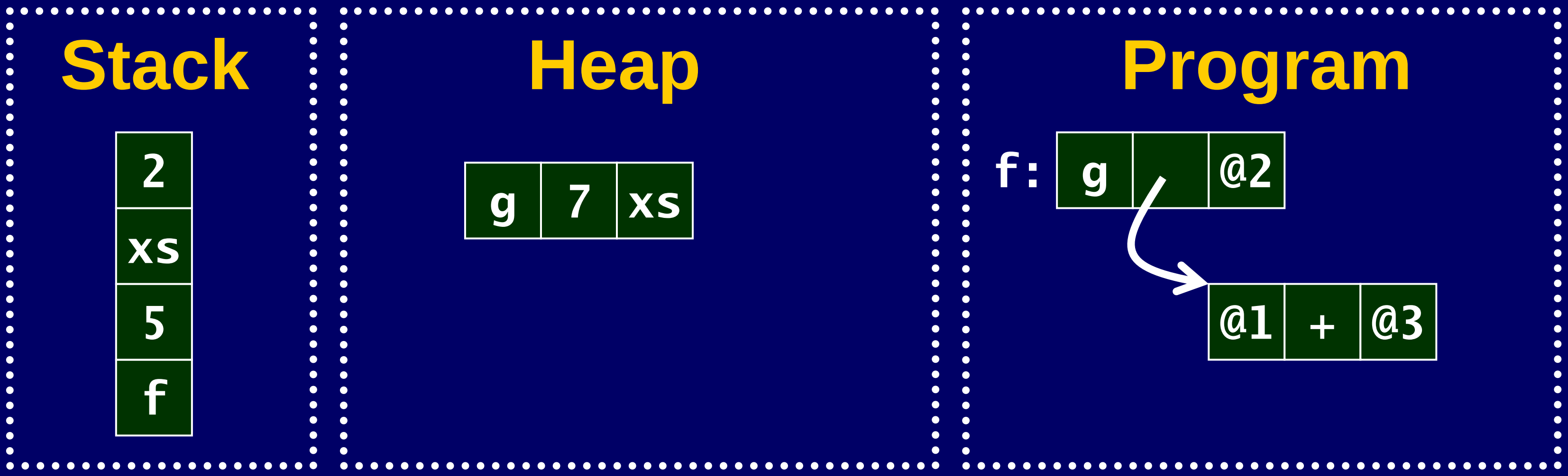
Primitive redexes

Application of **`f`** results in the ***primitive redex*** **`5+2`** being instantiated on the heap.



Speculative evaluation

Idea: *at runtime, look at the arguments to a primitive function. If they are already evaluated, apply the primitive speculatively.*



Results and to-do list

Reduceron, September 2008

Wide Reduceron
(uses wide, parallel memories)

5x faster than

Narrow Reduceron
(single connection to memory)

Wide Reduceron
at 92MHz on Virtex-II FPGA

5x slower than

GHC –O2
(advanced optimising compiler)
at 2800MHz on Pentium-4 PC

(On “symbolic programs”)

Improvements, March 2009

Program	**Speed-up**
Queens	2.1
Queens_2	2.9
PermSort	2.9
MSS	2.7
PropInsert	3.0
Sudoku	4.0
Adjoxo	3.1
While	2.8
Clausify	3.6
Average	**3.0**

So now within a factor of 2 of leading Haskell implementation.

To-do list

- Critical path reduction
- Parallel garbage collection (low vs. high-level)
- Compile-time optimisation
  - Supercompilation (Neil Mitchell, Jason Reich)
- Speculative evaluation of primitive redexes
- Dual-core Reduceron
- Larger, off-chip heap?
- Show off the *description language*!