Data Parallel Programming in Haskell

An Overview

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Includes joint work with
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Ben Lippmeier
Trevor McDonell
Simon Peyton Jones

Ubiquitous Parallelism

http://en.wikipedia.org/wiki/File:Cray_Y-MP_GSFC.jpg

venerable supercomputer

It's parallelism

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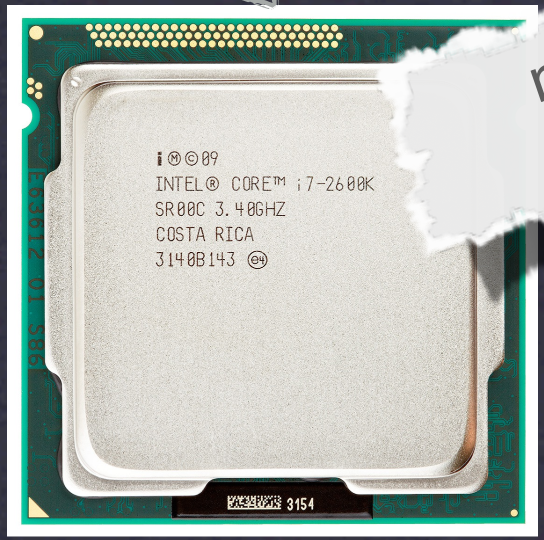

multicore CPU

http://en.wikipedia.org/wiki/File:Intel_CPU_Core_i7_2600K_Sandy_Bridge_top.jpg

multicore GPU

http://en.wikipedia.org/wiki/File:GeForce_GT_545_DDR3.jpg

It's parallelism

...but not as we know it!

Our goals

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- Exploit parallelism of commodity hardware easily:
  - Performance is important, but…
  - …productivity is more important.

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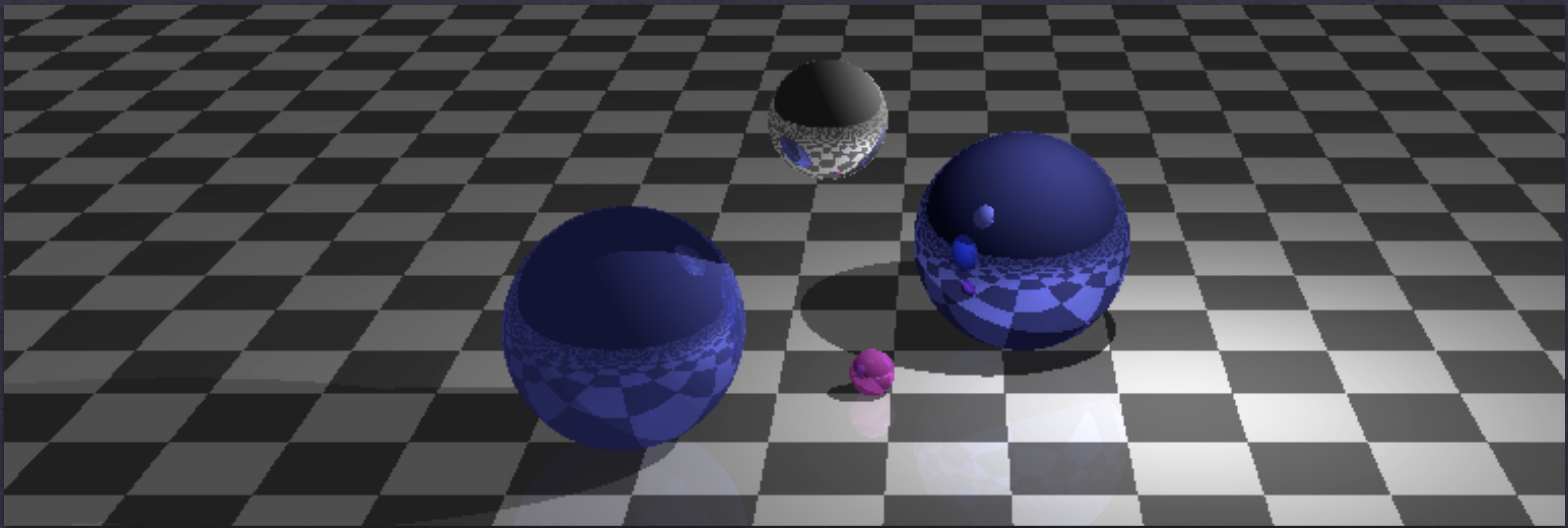
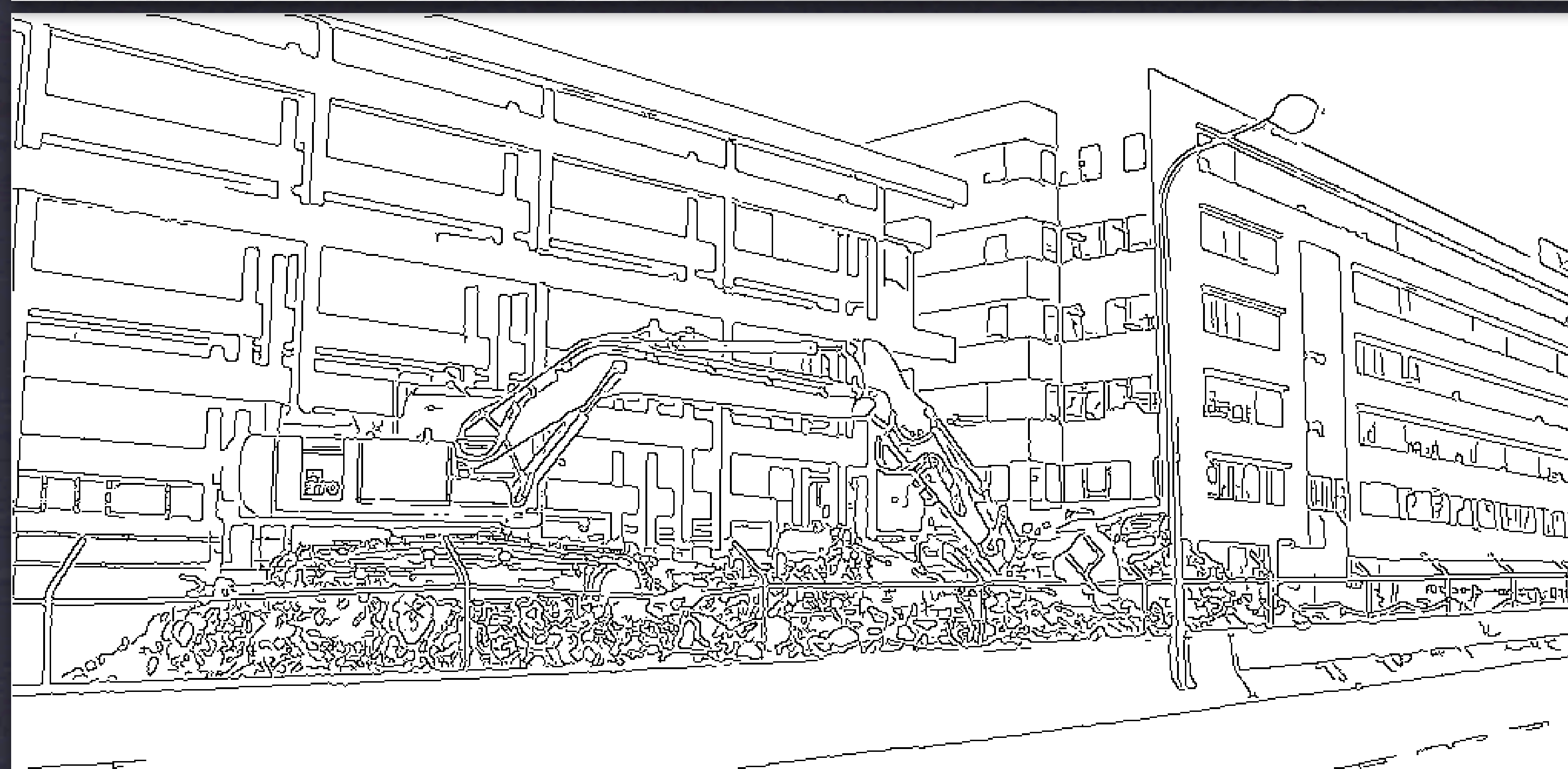
- Semi-automatic parallelism
  - Programmer supplies a parallel algorithm
  - No explicit concurrency (no concurrency control, no races, no deadlocks)



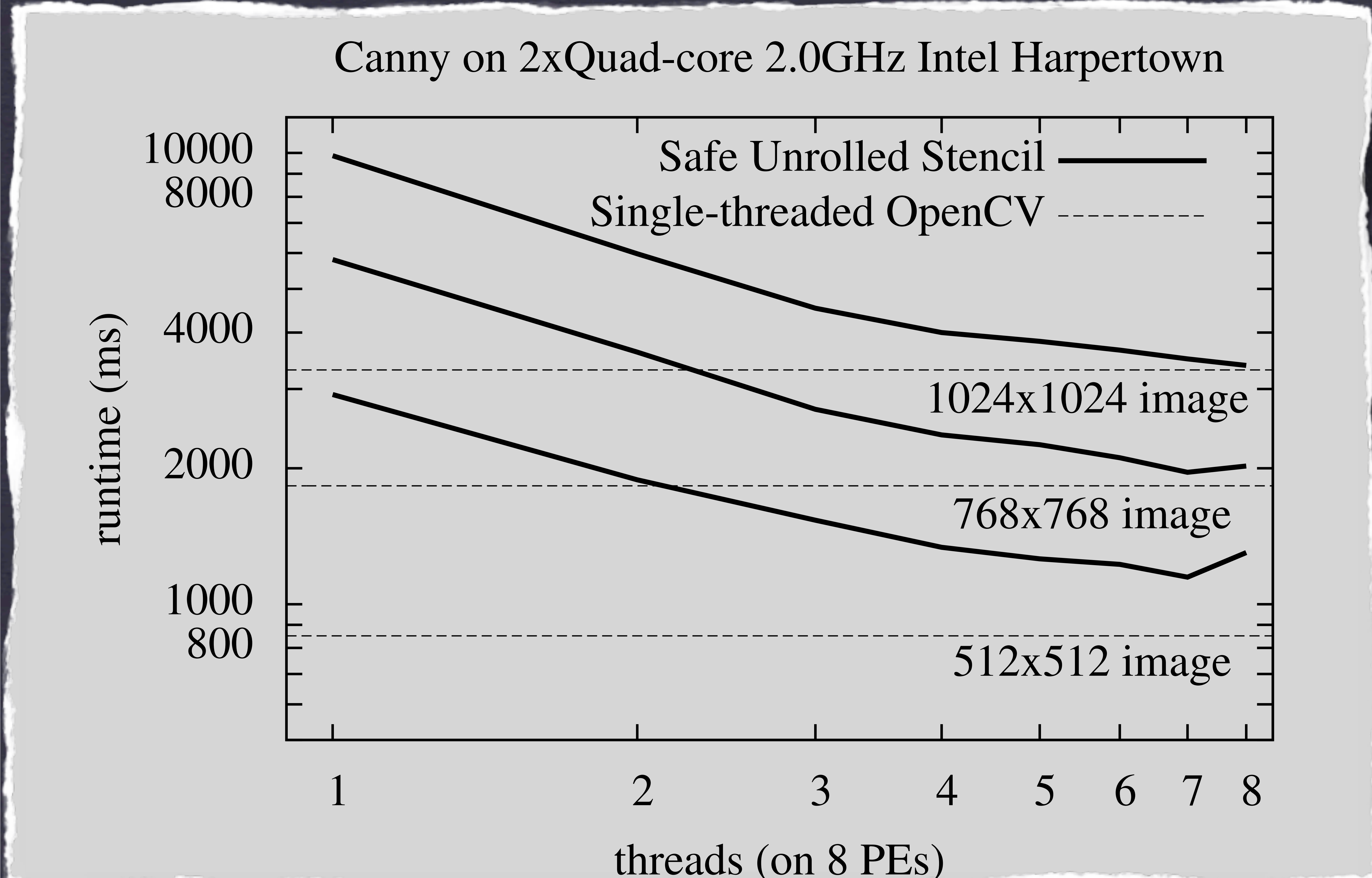
Graphics [Haskell 2012a]

Ray tracing



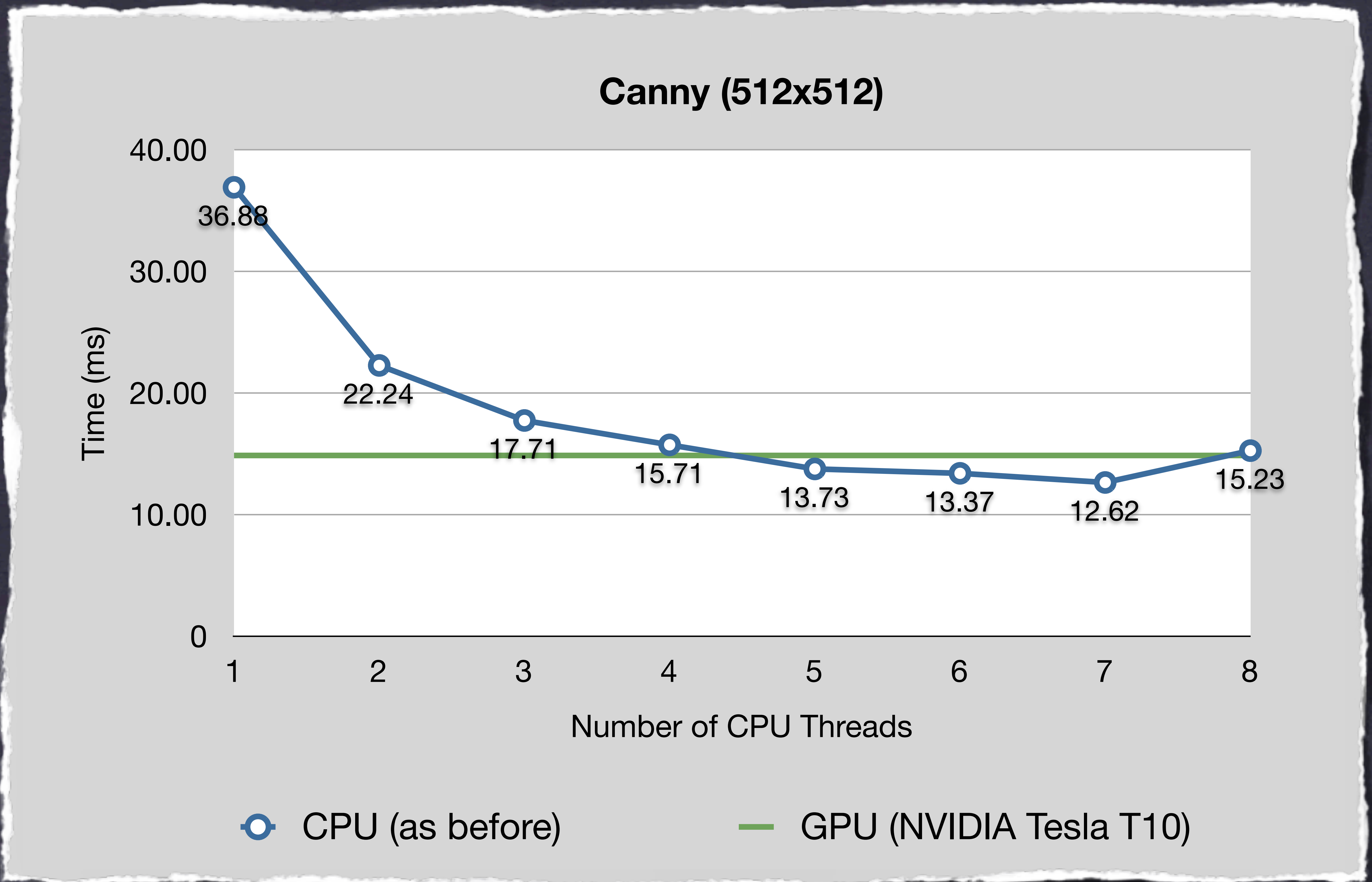
Computer Vision [Haskell 2011]

Edge detection



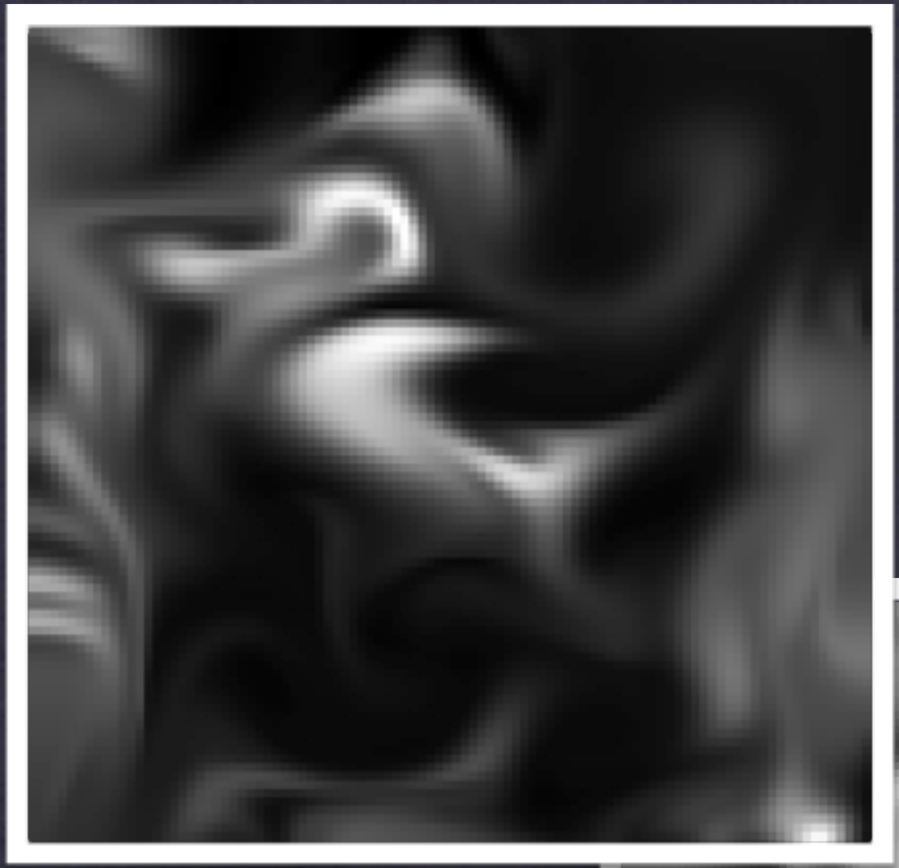
Runtimes for Canny edge detection (100 iterations)

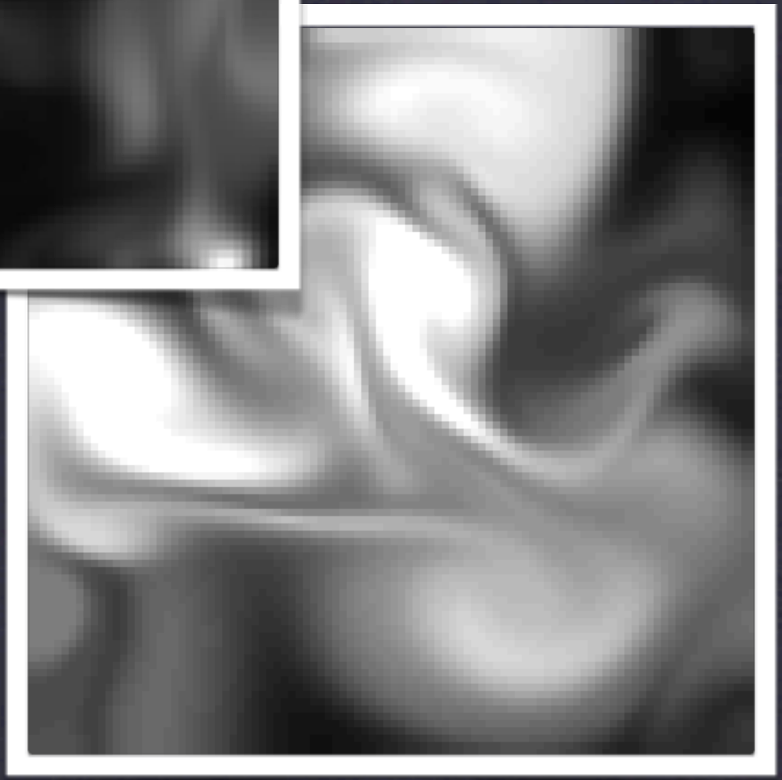
OpenCV uses SIMD-instructions, but only one thread



Canny edge detection: CPU versus GPU parallelism

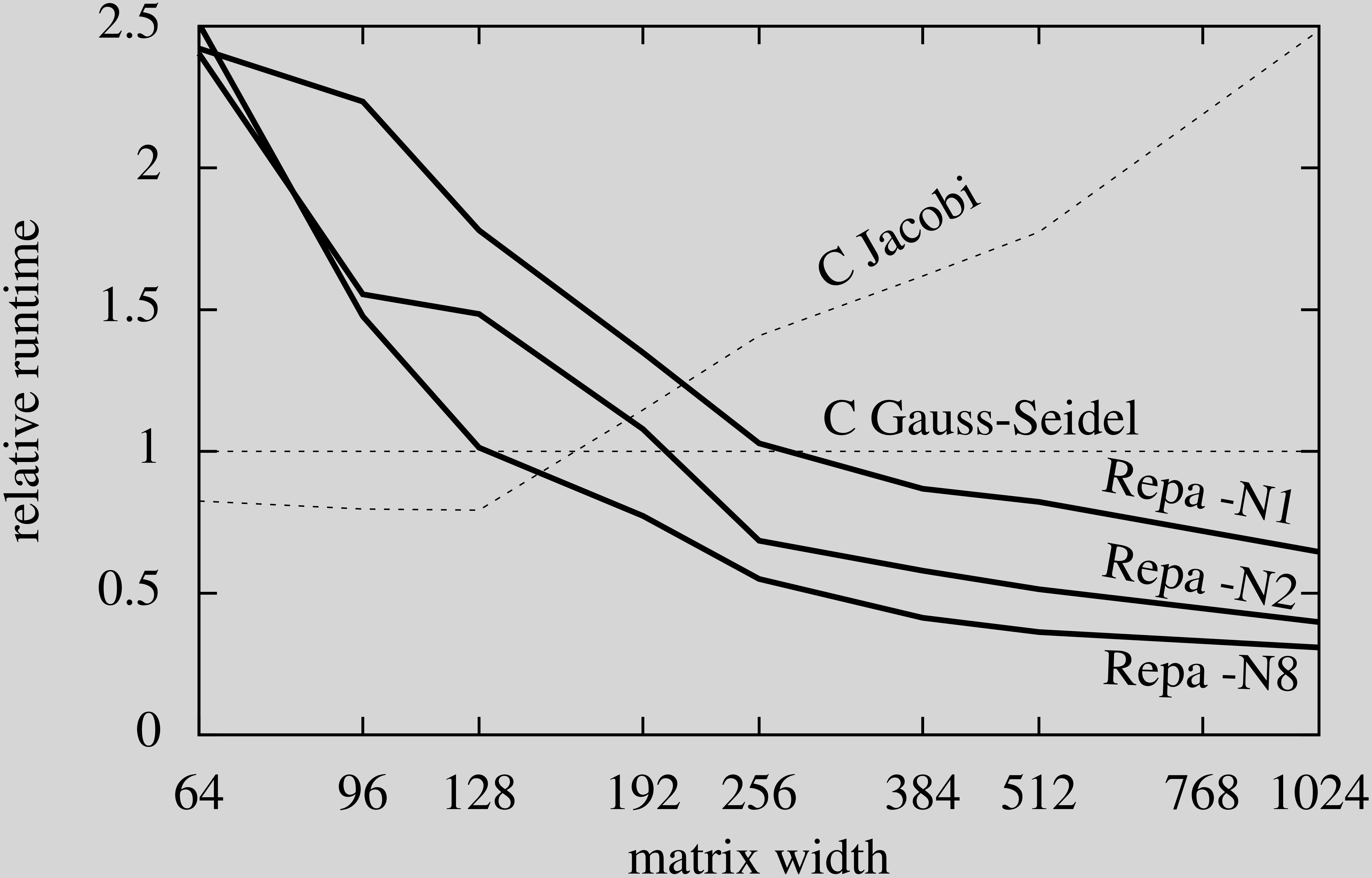
GPU version performs post-processing on the CPU





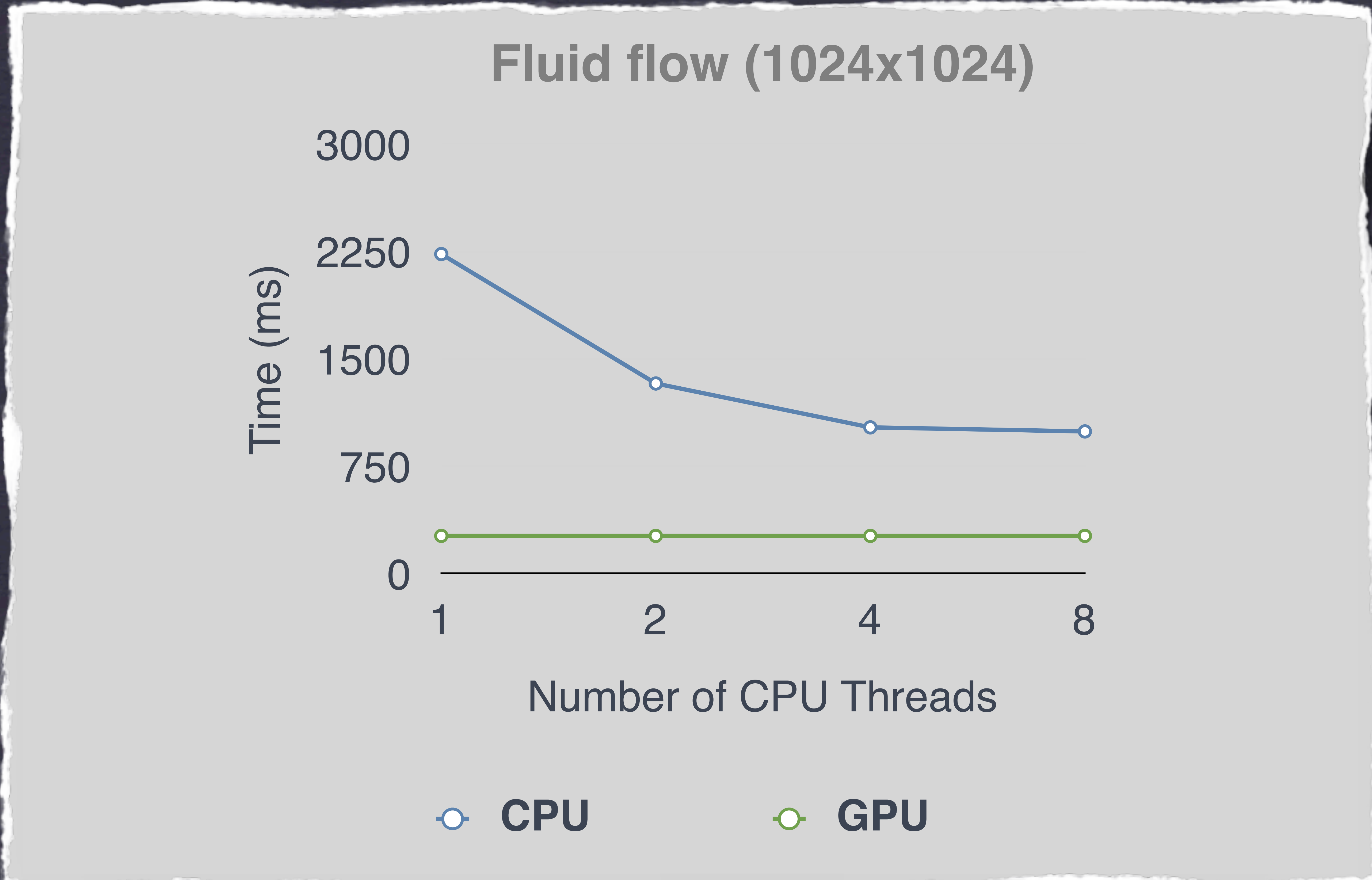
Physical Simulation [Haskell 2012a]

Fluid flow



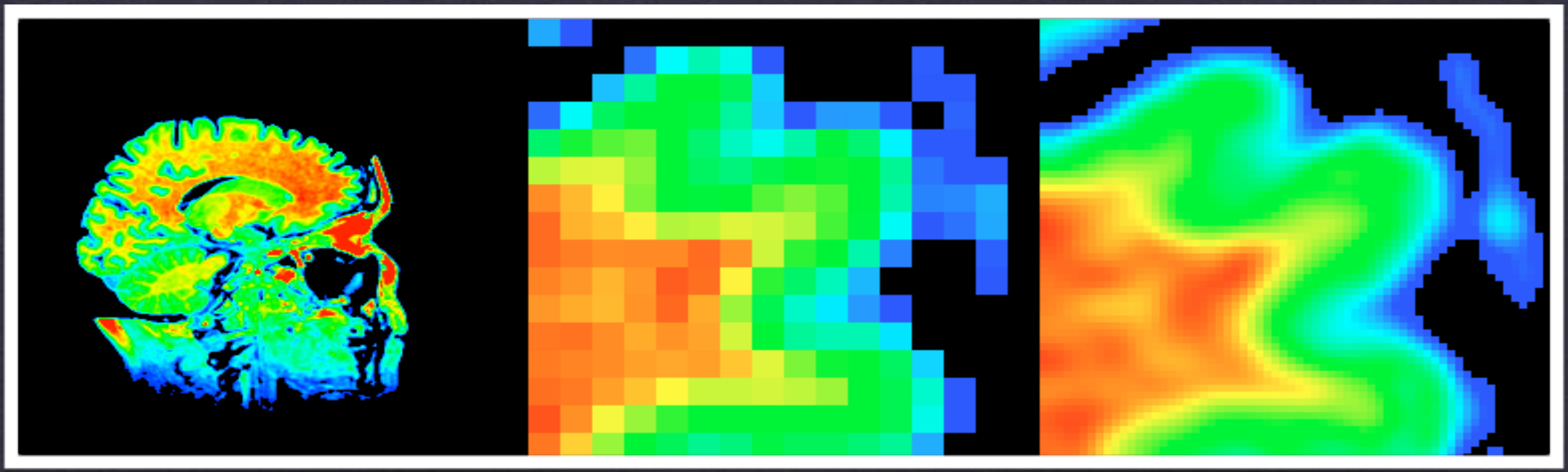
Runtimes for Jos Stam's Fluid Flow Solver

We can beat C!



Jos Stam's Fluid Flow Solver: CPU versus GPU Performance

GPU beats the CPU (includes all transfer times)



Medical Imaging [Haskell 2012a]

Interpolation of a slice though a 256 × 256 × 109 × 16-bit data volume of an MRI image

Functional Parallelism

Our ingredients

- Control effects, not concurrency
- Types guide data representation and behaviour
- Bulk-parallel aggregate operations

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PLS

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Declarative control of operational pragmatics

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Declarative control of operational pragmatics

Data parallelism

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Purity & Types

Purity and parallelism

```
processList :: [Int] -> ([Int], Int)
processList list = (sort list, maximum list)
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Purity and parallelism

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function body

PLS

Purity and parallelism

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result type

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- Purity: function result depends only on arguments

Purity and parallelism

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- **Purity:** function result depends only on arguments
- **Parallelism:** execution order only constrained by explicit data dependencies

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By default pure

Types track purity

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Pure = no effects	Impure = may have effects

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`processList :: [Int] -> ([Int], Int)`	`readFile :: FilePath -> IO String`

By default pure

Types track purity	
Pure = no effects	Impure = may have effects
`Int`	`IO Int`
`processList ::` `  [Int] -> ([Int], Int)`	`readFile ::` `  FilePath -> IO String`

`(sort list, maximum list)`	`copyFile fn1 fn2 =`
	` do`
	`   data <- readFile fn1`
	`   writeFile fn2 data`

Types guide execution

Datatypes for parallelism

- For bulk-parallel, aggregate operations, we introduce a new datatype:

```
Array r sh e
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Representation

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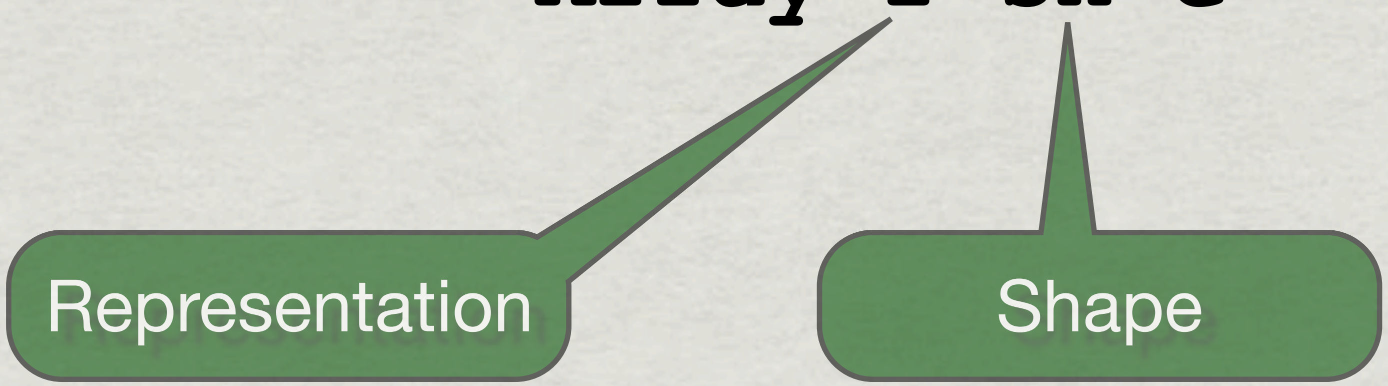

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Representation

Shape

Element type

Array r sh e

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- Representation: determined by a type index; e.g.,
  - `D` — delayed array (represented as a function)
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  - `DIM0`, `DIM1`, `DIM2`, and so on

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  - `D` — delayed array (represented as a function)
  - `U` — unboxed array (manifest C-style array)
- Shape: dimensionality of the array
  - `DIM0`, `DIM1`, `DIM2`, and so on
- Element type: stored in the array
  - Primitive types (`Int`, `Float`, etc.) and tuples

```haskell
zipWith :: (Shape sh, Source r1 a, Source r2 b)
        => (a -> b -> c)
        -> Array r1 sh a
        -> Array r2 sh b
        -> Array D sh c
```

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Delayed result

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Pure function to be used in parallel

Delayed result

Pocessed arrays

```
type PC5
   = P C (P (S D)(P (S D)(P (S D)(P (S D) X))))
mapStencil2 :: Source r a
            => Boundary a
            -> Stencil DIM2 a
            -> Array r DIM2 a
            -> Array PC5 DIM2 a
```

```
zipWith :: (Shape sh, Source r1 a, Source r2 b)
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Partitioned result

A simple example — dot product

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```
dotp v w = sumAll (zipWith (*) v w)
```

A simple example — dot product

```
type Vector r e = Array r DIM1 e

dotp :: (Num e, Source r1 e, Source r2 e)
     => Vector r1 e -> Vector r2 e -> e
```

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A simple example — dot product

Elements are any type of numbers…

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A simple example — dot product

Elements are any type of numbers…

…suitable to be read from an array

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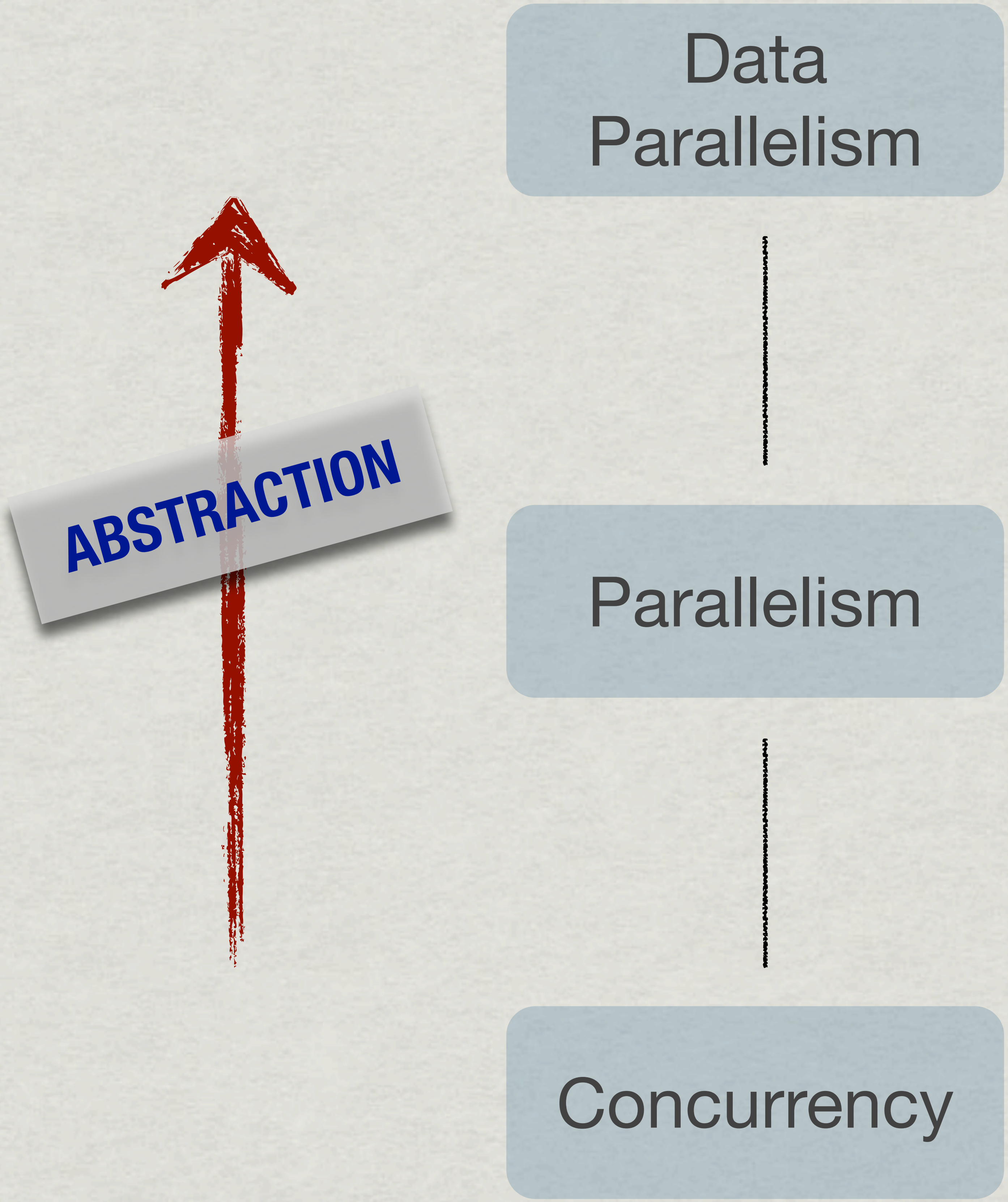
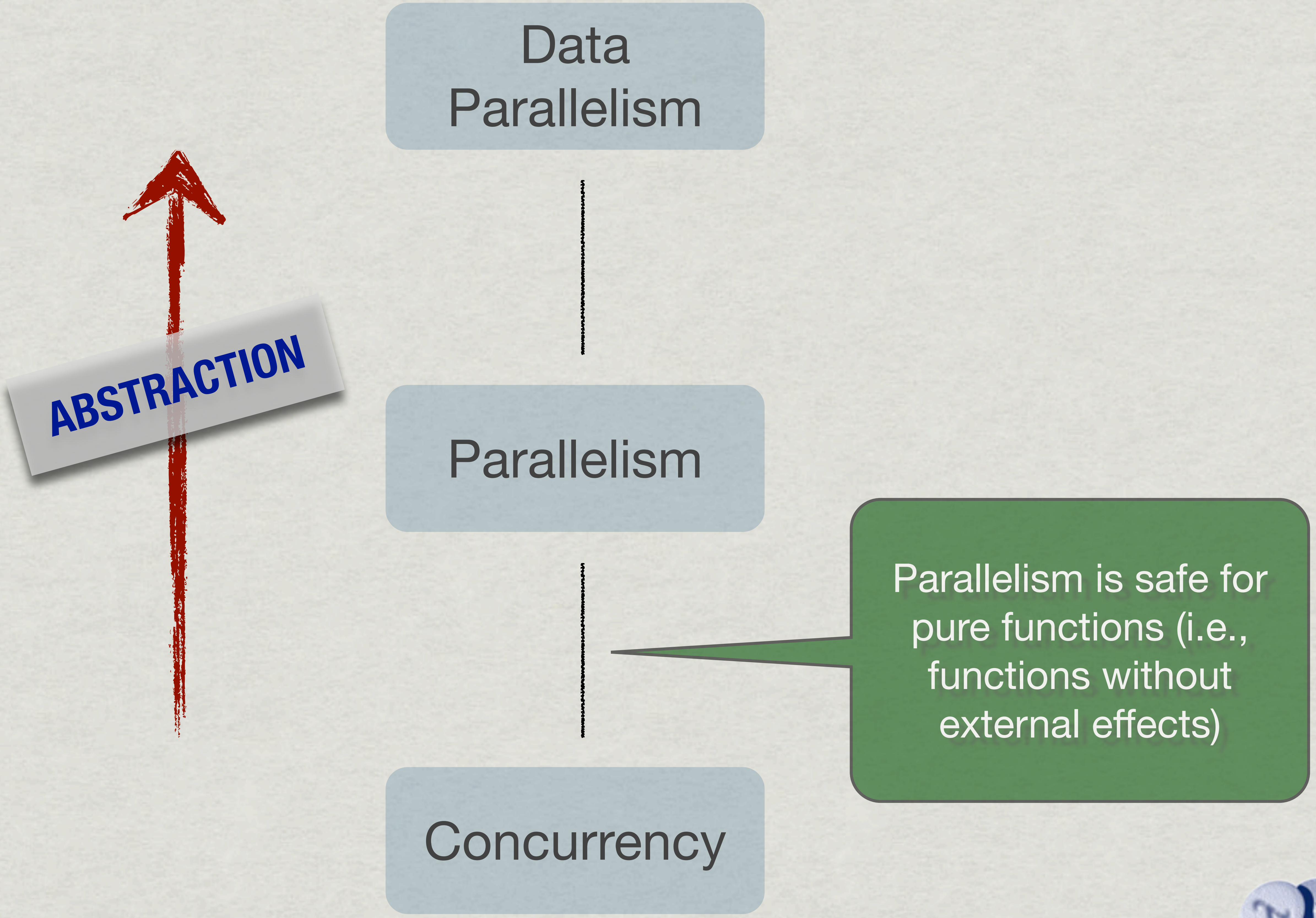

Data Parallelism
Parallelism
Concurrency
ABSTRACTION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Parallelism is safe for pure functions (i.e., functions without external effects)

PLS

ABSTRACTION

Data Parallelism

Collective operations have got a single conceptual thread of control

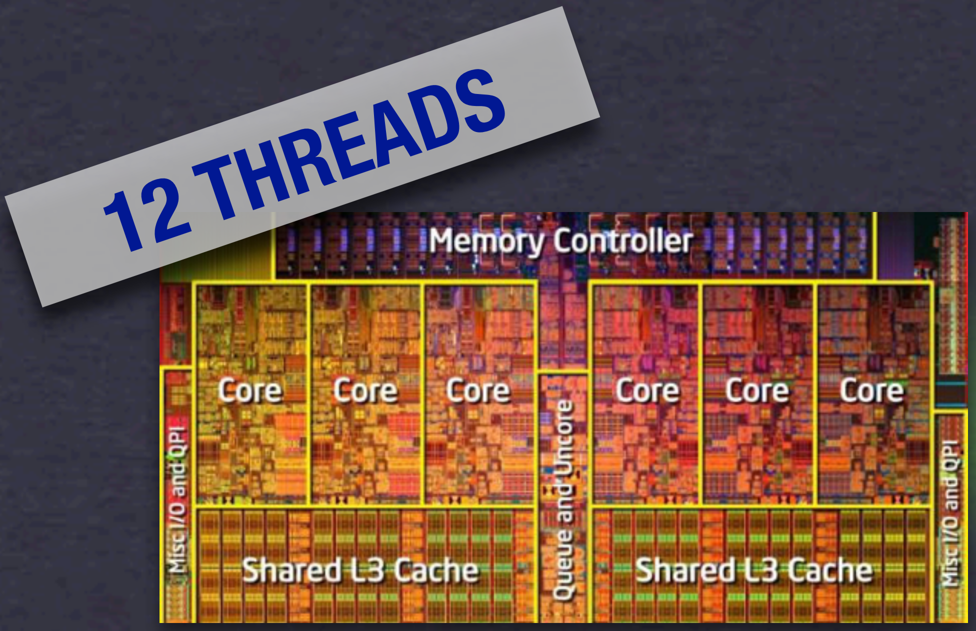
Parallelism

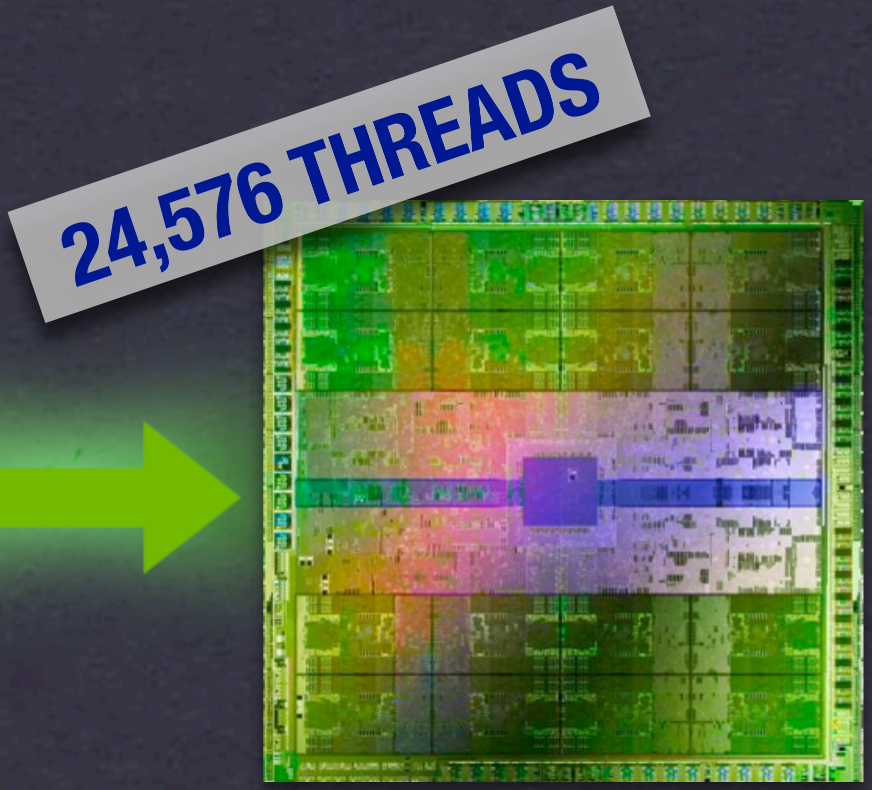
Parallelism is safe for pure functions (i.e., functions without external effects)

Concurrency

PLS

Types &
Embedded Computations





Core i7 970
CPU

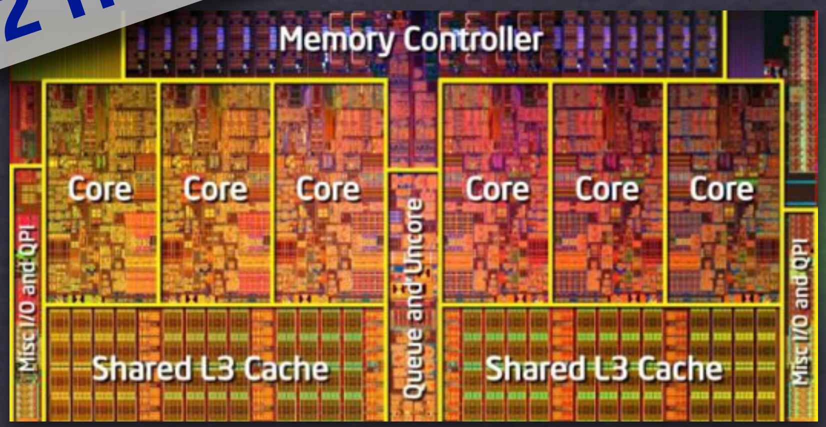
NVIDIA GF100
GPU

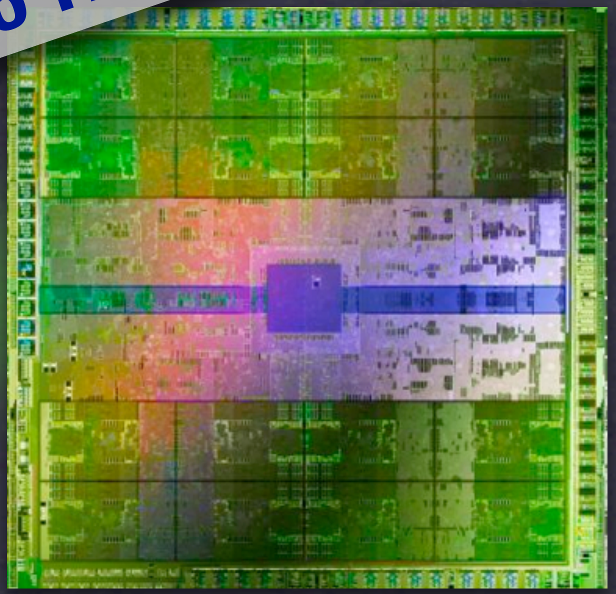
Coarse-grained Versus Fine-grained Parallelism

GPUs require careful program tuning

12 THREADS

24,576 THREADS





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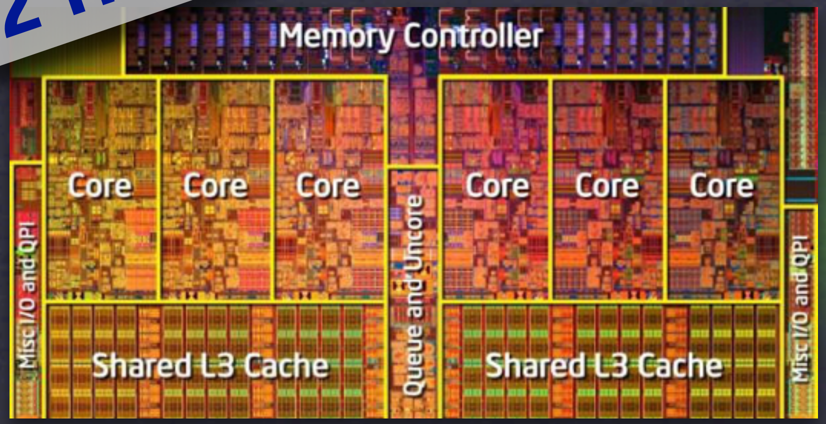

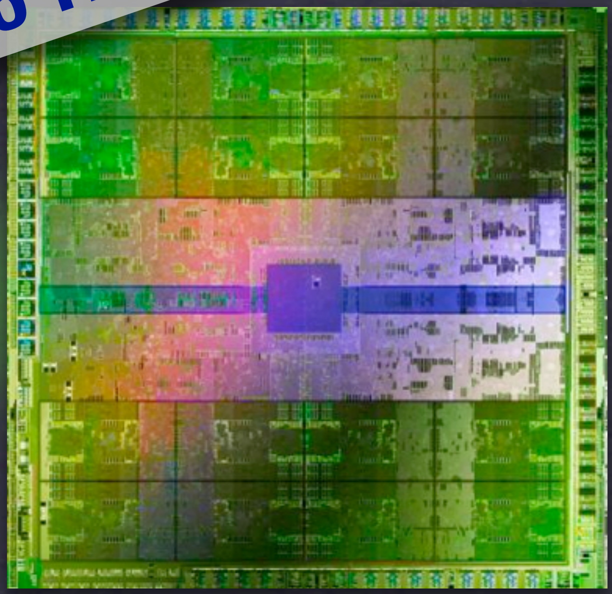

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- **Latency hiding:** optimised for regular memory access patterns
- Optimise memory access

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Code generation for embedded code

- Embedded DSL
  - Restricted control flow
  - First-order GPU code
- Generative approach based on combinator templates

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PLS

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✓ limited control structures

✓ hand-tuned access patterns

[DAMP 2011]

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Embedded GPU computations

Dot product

```
dotp :: Vector Float -> Vector Float
     -> Acc (Scalar Float)
dotp xs ys
  = let
      xs' = use xs
      ys' = use ys
    in
    fold (+) 0 (zipWith (*) xs' ys')
```

Embedded GPU computations

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Haskell array

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Lift Haskell arrays into EDSL — may trigger host➙device transfer

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Haskell array

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Embedded array computations

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Nested Data Parallelism

Modularity

- Standard (Fortran, CUDA, etc.) is flat, regular parallelism
- Same for our libraries for functional data parallelism for multicore CPUs (Repa) and GPUs (Accelerate)
- But we want more…

```
smvm :: SparseMatrix -> Vector -> Vector
smvm sm v = [: sumP (dotp sv v) | sv <- sm :]
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Parallel array comprehension

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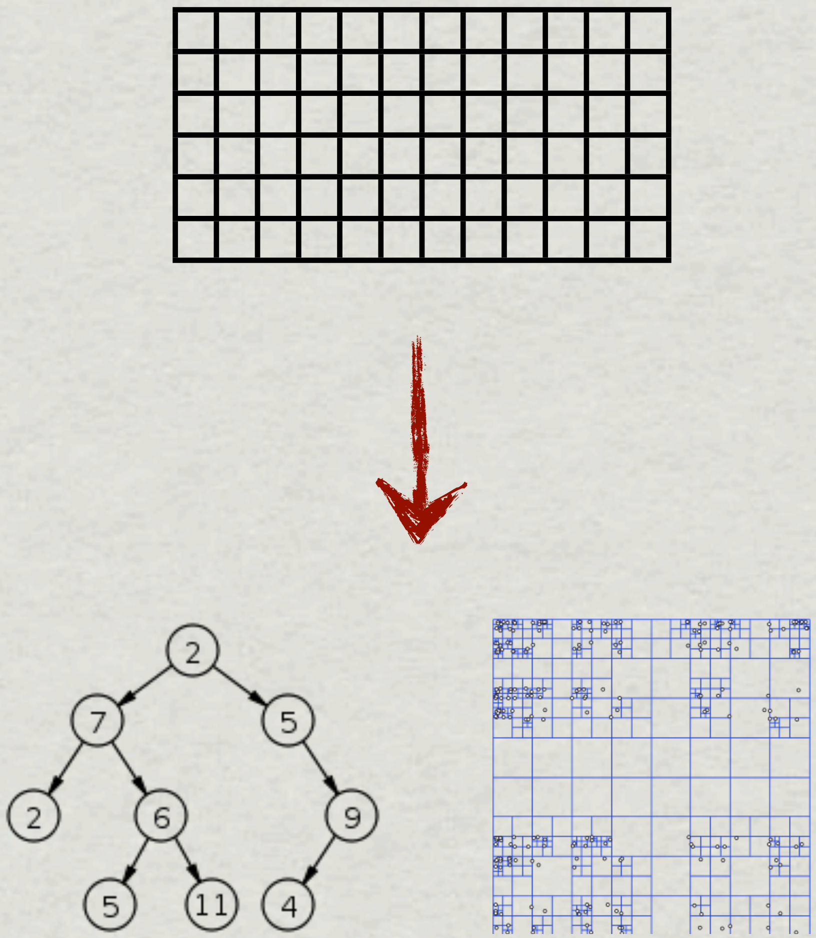
Nested parallelism!

Nested parallelism?

Regular, flat data parallelism is not sufficient!

Nested parallelism



- Modular
- Irregular, nested data structures
  - Sparse structures, tree structures
  - Hierachrchical decomposition
- Nesting to arbitrary, dynamic depth: divide & conquer
- Lots of compiler work: still very experimental! [FSTTCS 2008, ICFP 2012, Haskell 2012b]

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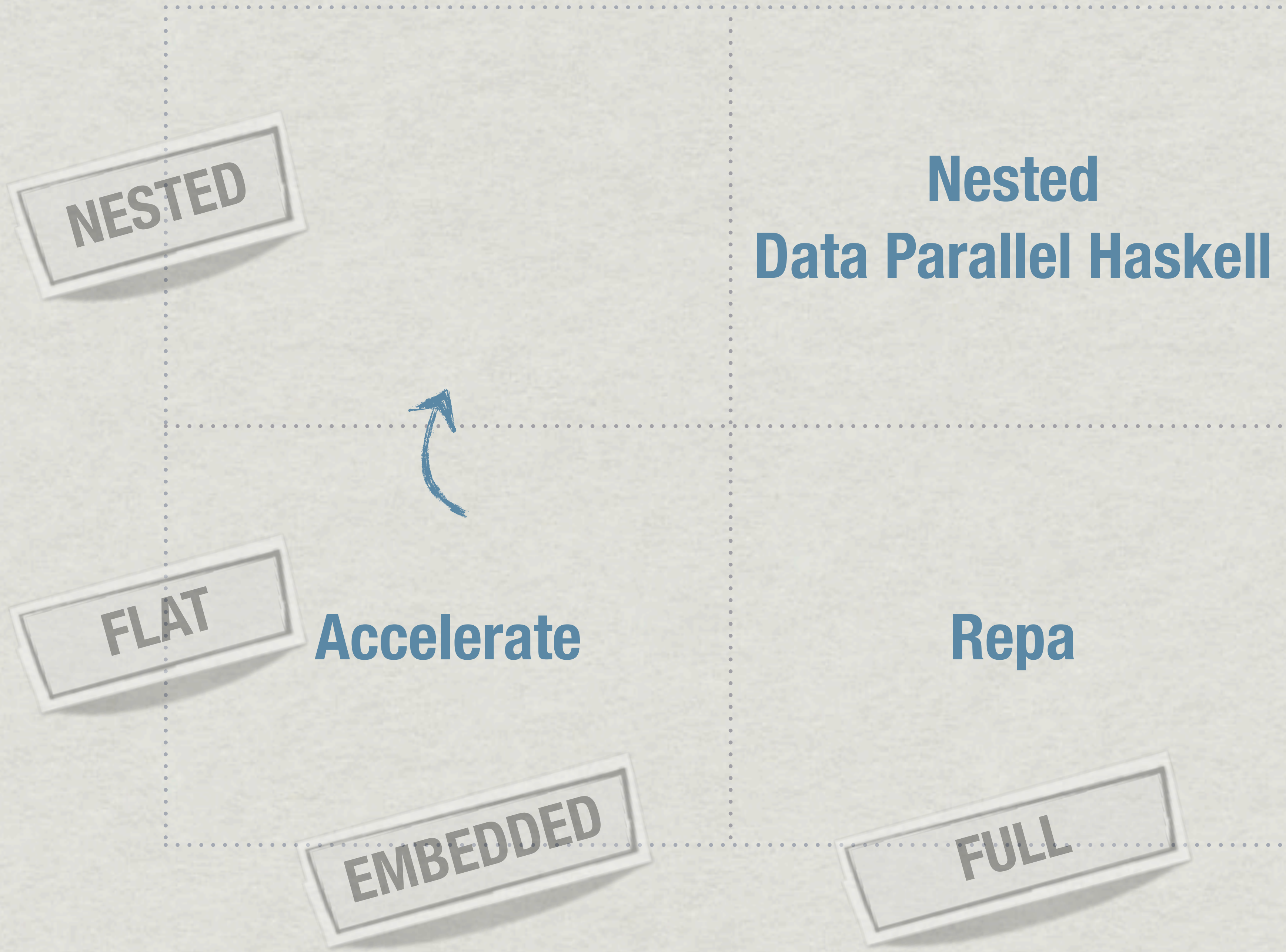
NESTED
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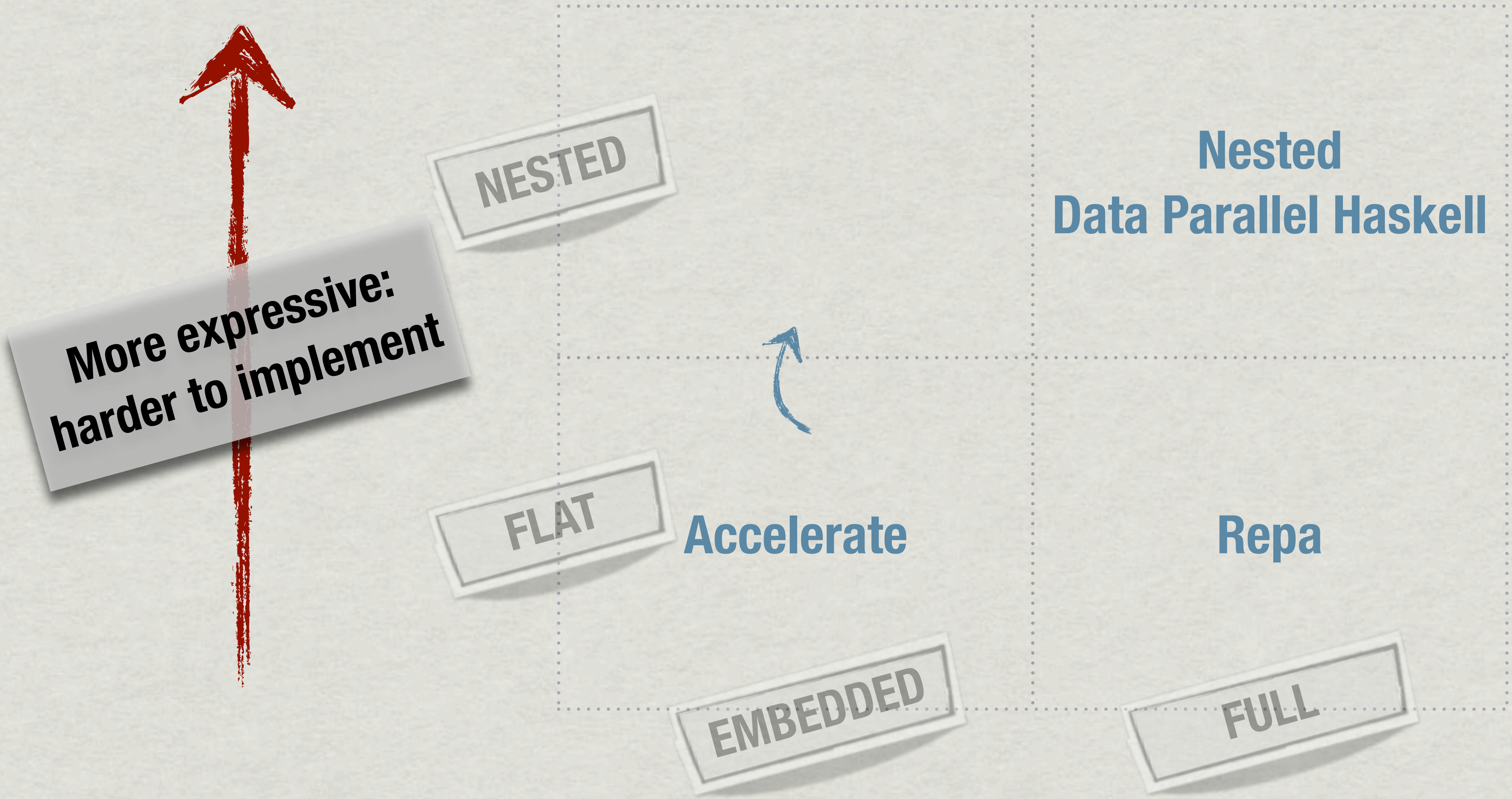

More expressive:
harder to implement
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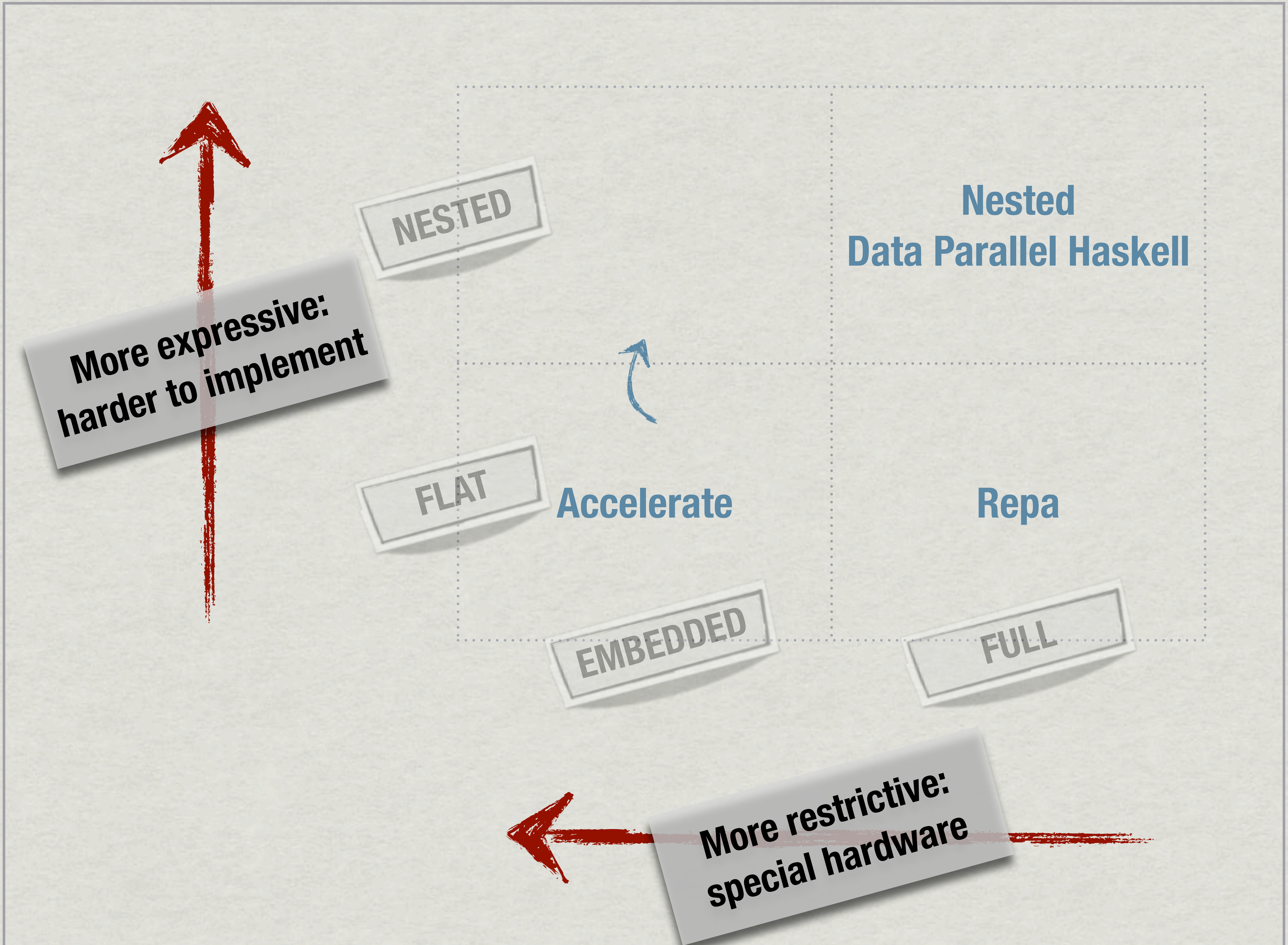
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PLS

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- Types separate pure from effectful code
- Types guide operational behaviour (data representation, use of parallelism, etc.)
- Types identify restricted code for specialised hardware, such as GPUs
- Types guide parallelising program transformations

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Summary

Blog: http://justtesting.org/
Twitter: @TacticalGrace

- Core ingredients
  - Control purity, not concurrency
  - Types guide representations and behaviours
  - Bulk-parallel operations
- Get it
  - Latest Glasgow Haskell Compiler (GHC)
  - Repa, Accelerate & DPH packages from Hackage (Haskell library repository)

PLS

Thank you!

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[Haskell 2012b] *Vectorisation Avoidance*. Keller, Chakravarty, Lippmeier, Leshchinskiy & Peyton Jones. In Proceedings of "ACM SIGPLAN Haskell Symposium 2012", ACM Press, 2012. Forthcoming.