# Bridging the Divide: A *New* Tool-Support Methodology for Programming Heterogeneous Multi-Core Machines

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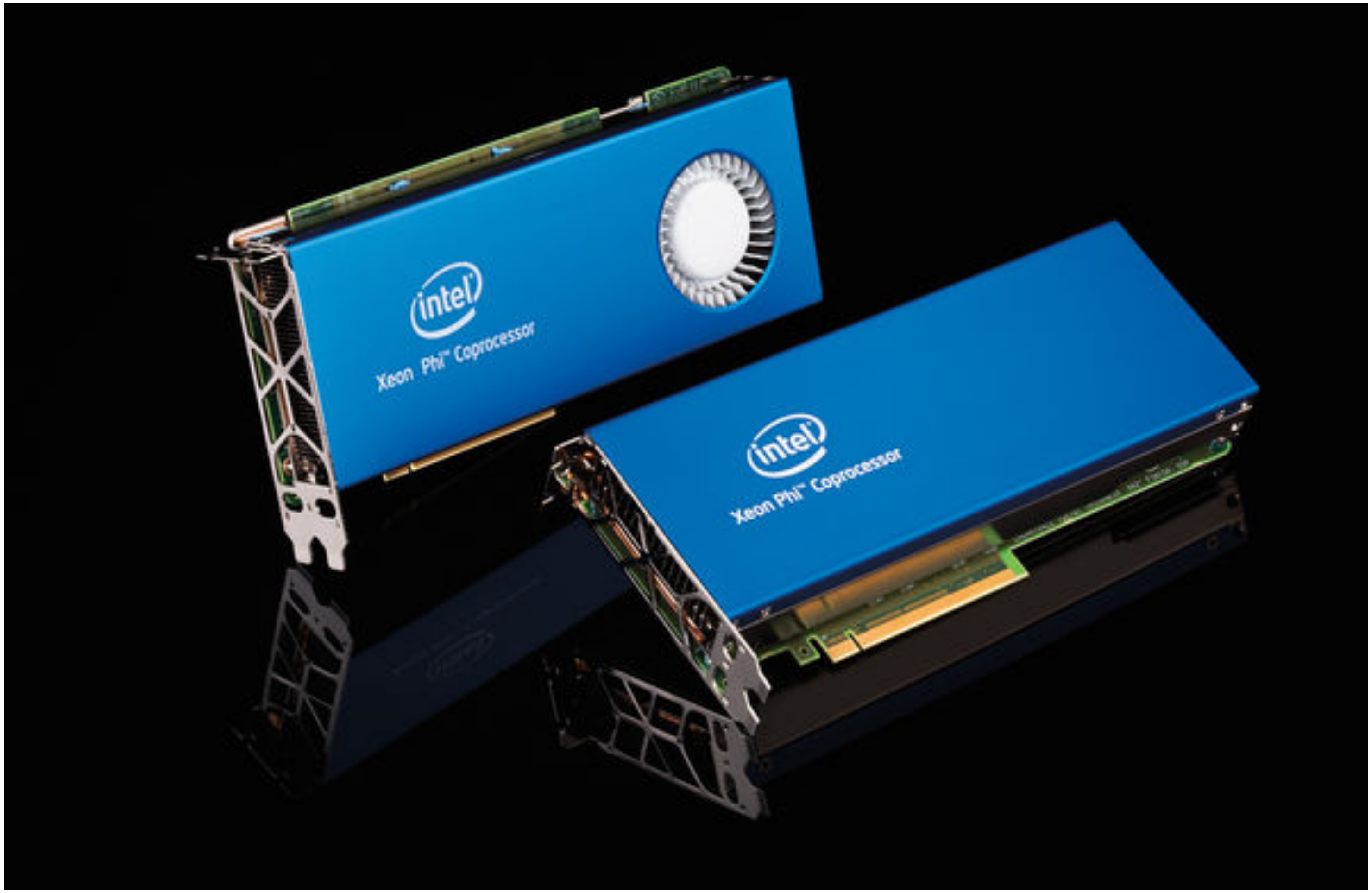
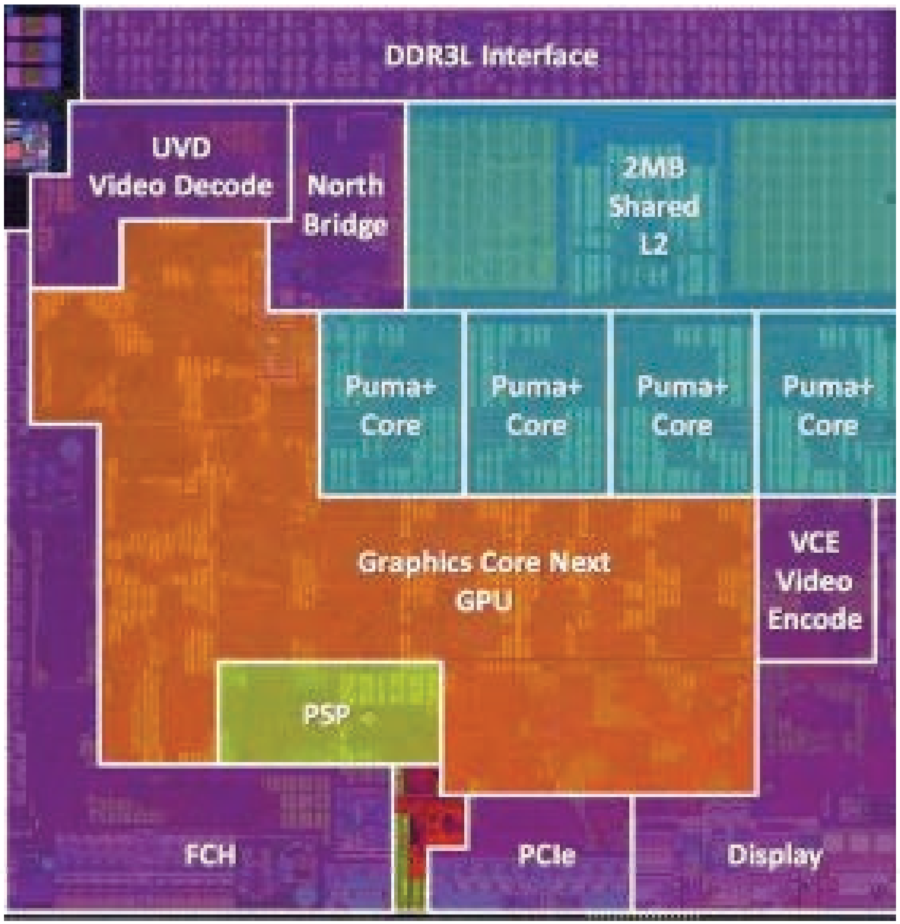
SEVENTH FRAMEWORK PROGRAMME

PARAPHRASE

# 2014: a ManyCore Odyssey



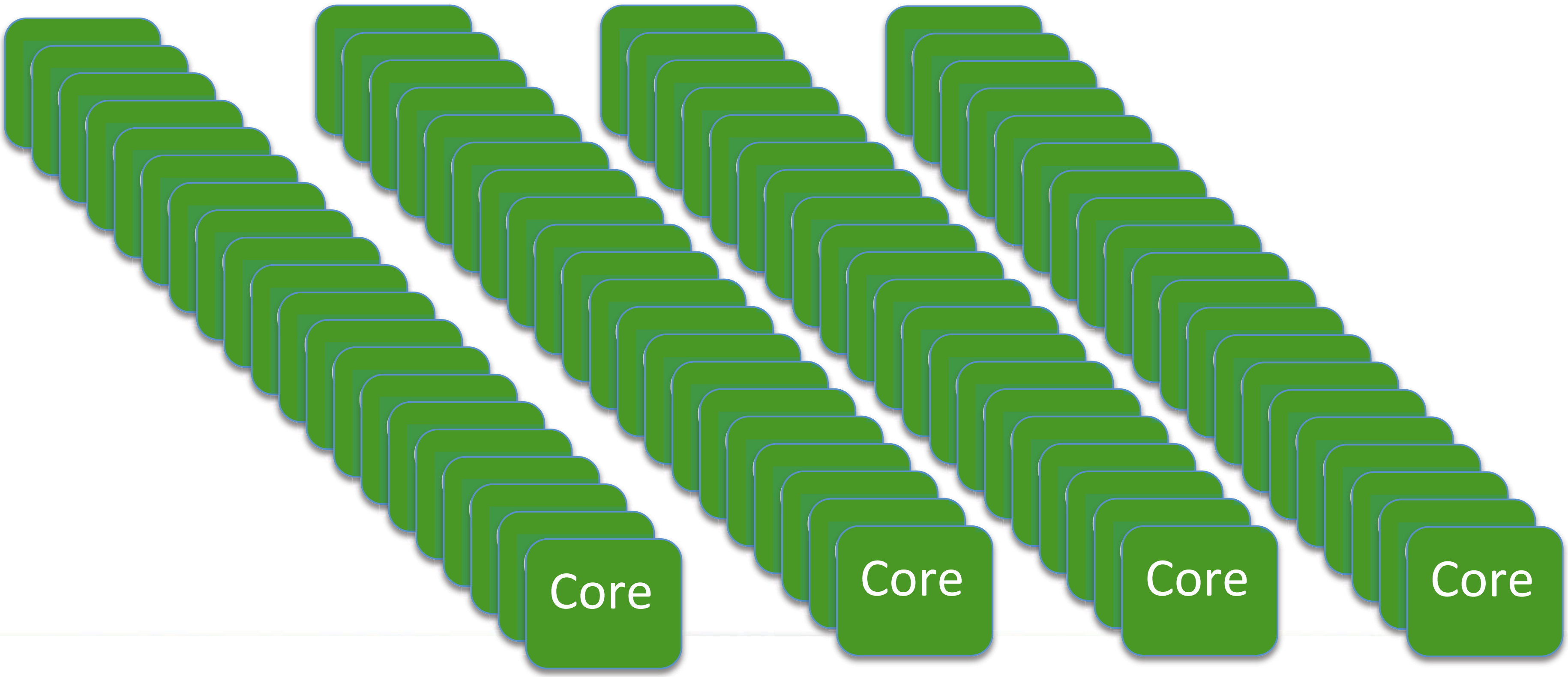
# AMD Mullins/Beema APU




- 4 Core x86 CPU
- 1 ARM PSP Security Core
- Graphics Core next to GPU with 128 cores
  - Used in e.g. Xbox 360
- Power consumption ~4.5W

# The Future: “megacore” computers?

- *Hundreds of thousands, or millions, of (small) cores*



# What will "megacore" computers look like?

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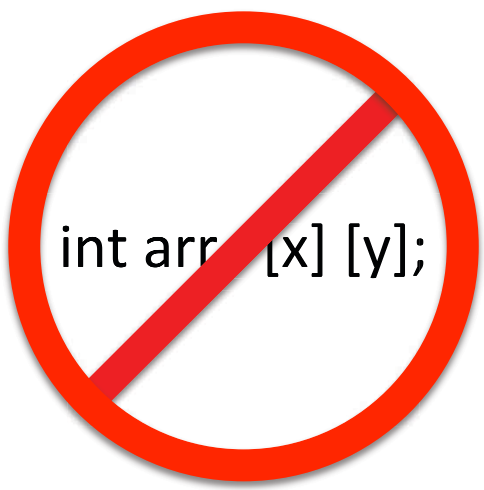
- **Probably *not* just scaled versions of today's multicore**
  - Perhaps hundreds of dedicated lightweight integer units
  - Hundreds of floating point units (enhanced GPU designs)
  - A *few* heavyweight general-purpose cores
  - Some specialised units for graphics, authentication, network etc
  - possibly *soft* cores (FPGAs etc)
  - ***Highly heterogeneous***

# What will "megacore" computers look like?

- **Probably *not* uniform shared memory**
  - NUMA is likely, even hardware distributed shared memory
  - or even message-passing systems on a chip
  - *shared-memory will not be a good abstraction*



# Laki (NEC Nehalem Cluster) and hermit (XE6)

**Laki**

- 700 dual socket Xeon 5560 2,8GHz ("Gainestown")
- 12 GB DDR3 RAM / node
- Infiniband (QDR)
- 32 nodes with additional Nvidia Tesla S1070
- Scientific Linux 6.0

**hermit (phase 1 step 1)**

- 38 racks with 96 nodes each
- 96 service nodes and 3552 compute nodes
- Each compute node will have 2 sockets AMD Interlagos @ 2.3GHz 16 Cores each leading to 113.664 cores
- Nodes with 32GB and 64GB memory reflecting different user needs
- 2.7PB storage capacity @ 150GB/s IO bandwidth
- External Access Nodes, Pre- & Postprocessing Nodes, Remote Visualization Nodes

# The Fastest Computer in the World

**Tianhe-2, Chinese National University of Defence Technology**

33.86 petaflops/s (June 17, 2013)
16,000 Nodes; each with 2 Ivy Bridge multicores and 3 Xeon Phis
**3,120,000 x86 cores in total!!!**

# It’s not just about large systems



- Even mobile phones are multicore
  - Samsung Exynos 5 Octa has 8 cores, 4 of which are “dark”
- Performance/energy tradeoffs mean systems will be increasingly parallel
- If we don’t solve the multicore challenge, then no other advances will matter!


ALL Future Programming will be Parallel!

# Parallel Hardware Today

- Computer hardware is getting more and more parallel
  - 64-core machines available off-the-shelf for a modest price
- It is also getting more and more heterogeneous
  - Any decent desktop machine comprises a multicore CPU and many-core GPU
  - Even mobile phones come with multiple GPUs


# The Manycore Challenge

"Ultimately, developers should start thinking about *tens, hundreds, and thousands* of cores *now* in their algorithmic development and deployment pipeline."

The **ONLY** important challenge in Computer Science (Intel)

will not ``automagically'' run

Also recognised as thematic priorities by EU and national funding bodies

**Patrick Leonard, Vice President for Product Development**
**Rogue Wave Software**

# But Doesn't that mean millions of threads on a megacore machine??

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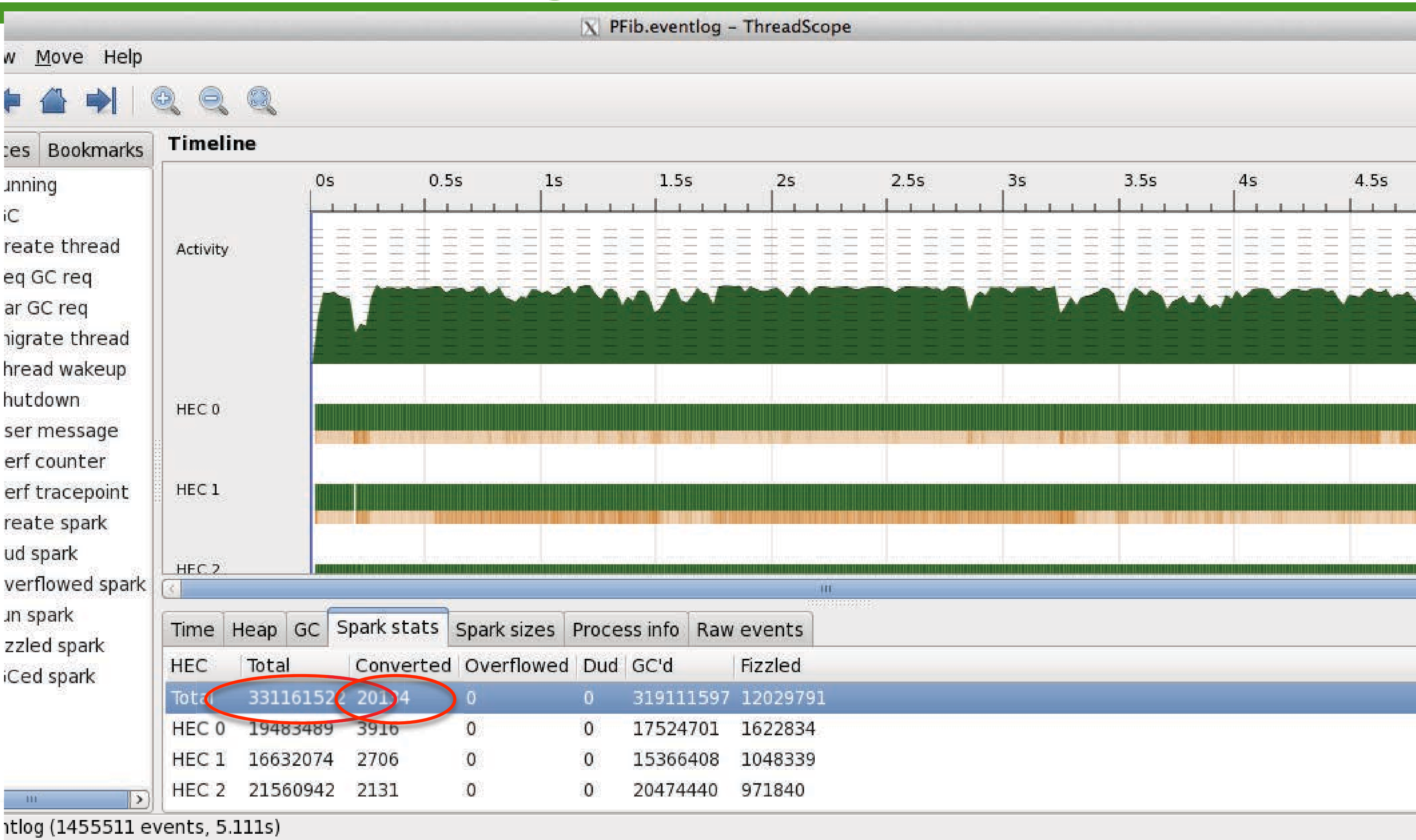

# Thinking Parallel

- **Fundamentally, programmers must learn to "think parallel"**
  - this requires new *high-level* programming constructs
    - perhaps dealing with hundreds of *millions* of threads
- **You cannot program effectively while worrying about deadlocks etc.**
  - they must be eliminated from the design!
- **You cannot program effectively while fiddling with communication etc.**
  - this needs to be packaged/abstracted!
- **You cannot program effectively without performance information**
  - this needs to be included as part of the design!

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SEVENTH FRAMEWORK PROGRAMME

**ParaPhrase Project: Parallel Patterns for Heterogeneous Multicore Systems (ICT-288570), 2011-2014, €4.2M budget**

**13 Partners, 8 European countries**

**UK, Italy, Germany, Austria, Ireland, Hungary, Poland, Israel**

**Coordinated by Kevin Hammond St Andrews**

AGH

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PARAPHRASE

# The ParaPhrase Approach

- Start bottom-up
  - identify (strongly hygienic) **COMPONENTS**
  - *using semi-automated refactoring*

*both legacy and new programs*

- Think about the **PATTERN** of parallelism
  - e.g. map(reduce), task farm, parallel search, parallel completion, ...

- **STRUCTURE** the components into a parallel program
  - ***turn the patterns into concrete (skeleton) code***
  - Take performance, **energy** etc. into account (multi-objective optimisation)
  - also using refactoring

- **RESTRUCTURE** if necessary! (also using refactoring)

# In This Talk…

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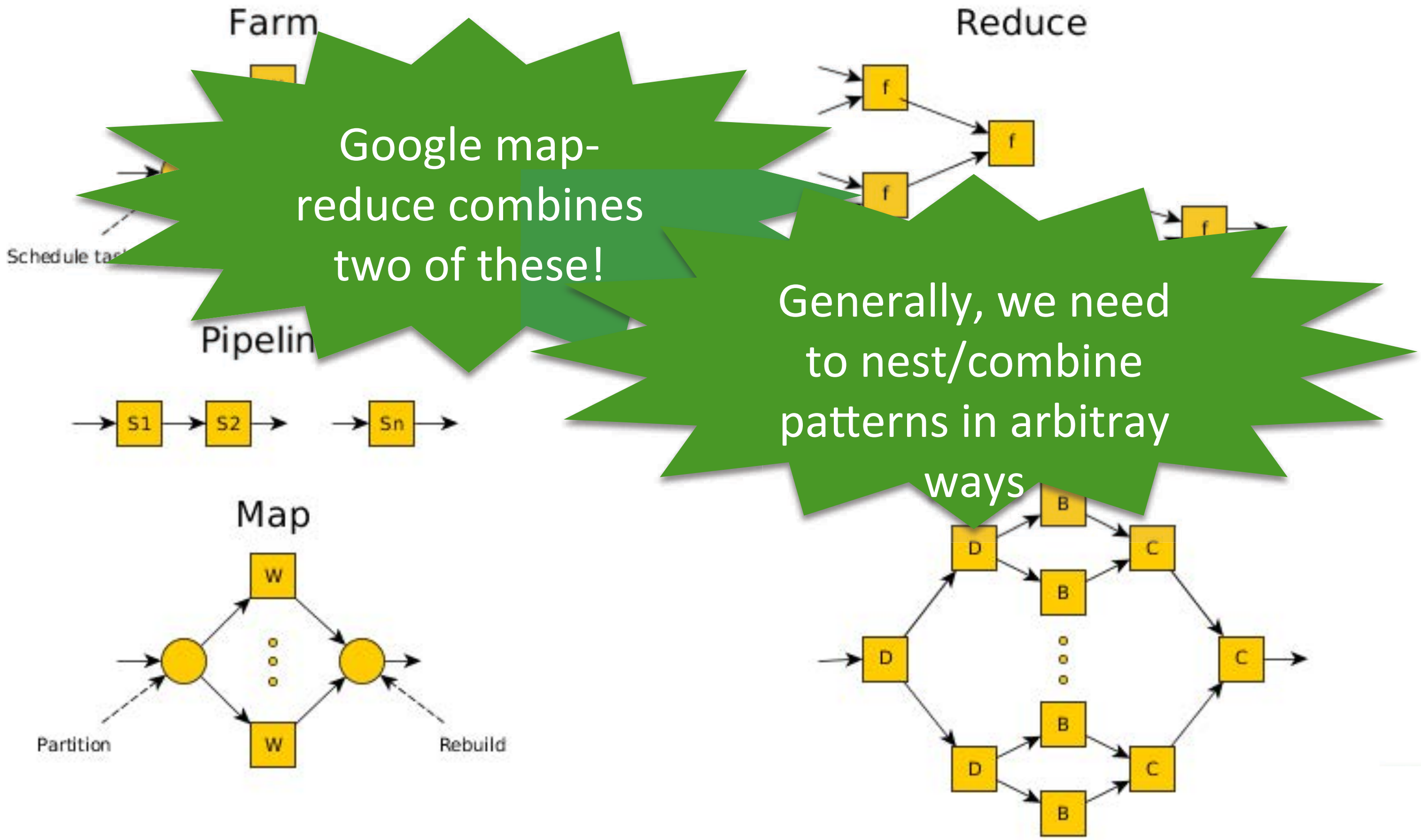
- Provide an Erlang skeleton library to make it easier to deal with parallelism
- Extend this library to deal with CPU/GPU systems
  - Heterogeneous Erlang skeletons
  - openCL bindings
- Provide refactoring Tool-Support to ease the introduction of the GPU code
- Show initial heterogeneous results for Erlang

# Some Common Patterns

- High-level abstract patterns of common parallel algorithms



# The *Skel* Library for Erlang

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- Skeletons implement specific parallel patterns
  - Pluggable templates
- **Skel** is a new (AND ONLY!) Skeleton library in Erlang
  - map, farm, reduce, pipeline, feedback
  - instantiated using **skel:do**
- ***Fully Nestable***
- **A DSL for parallelism**

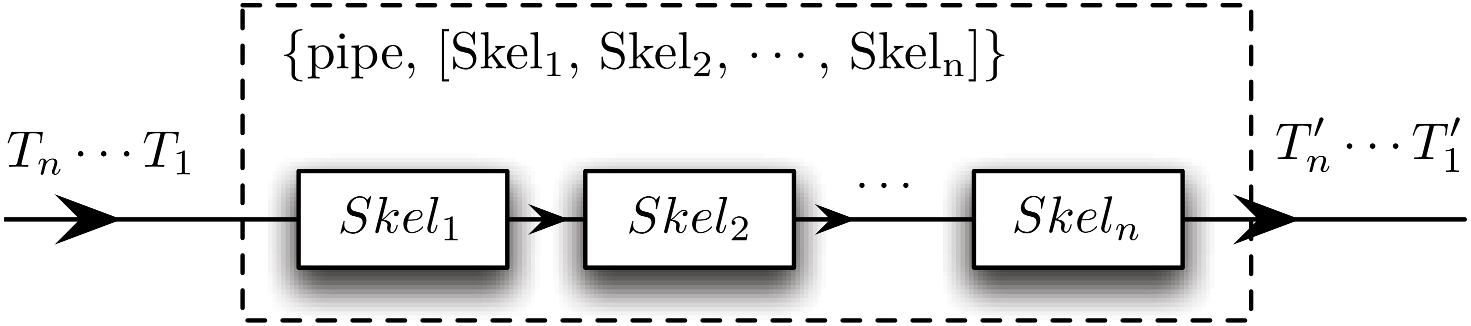
chrisb.host.cs.st-andrews.ac.uk/skel.html

https://github.com/ParaPhrase/skel

```
OutputItems = skel:do(Skeleton, InputItems).
```

# Parallel Pipeline Skeleton

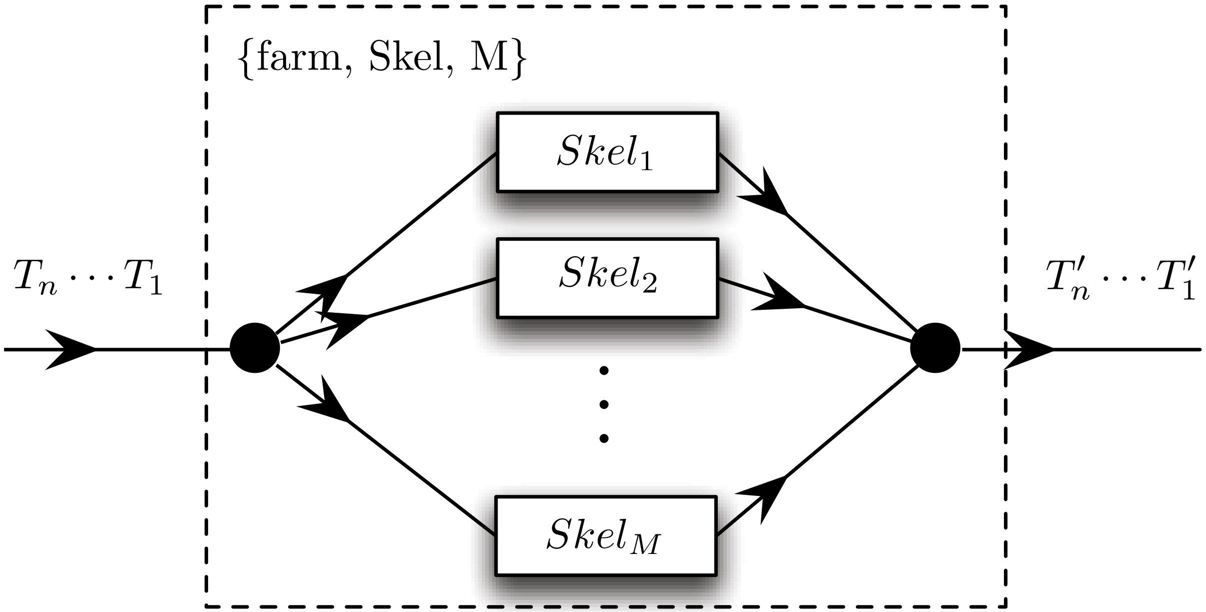
- Each stage of the pipeline can be executed in parallel
- The input and output are streams




```
Skel:do([{pipe,[Skel1, Skel2,..,SkelN]}], Inputs).
```

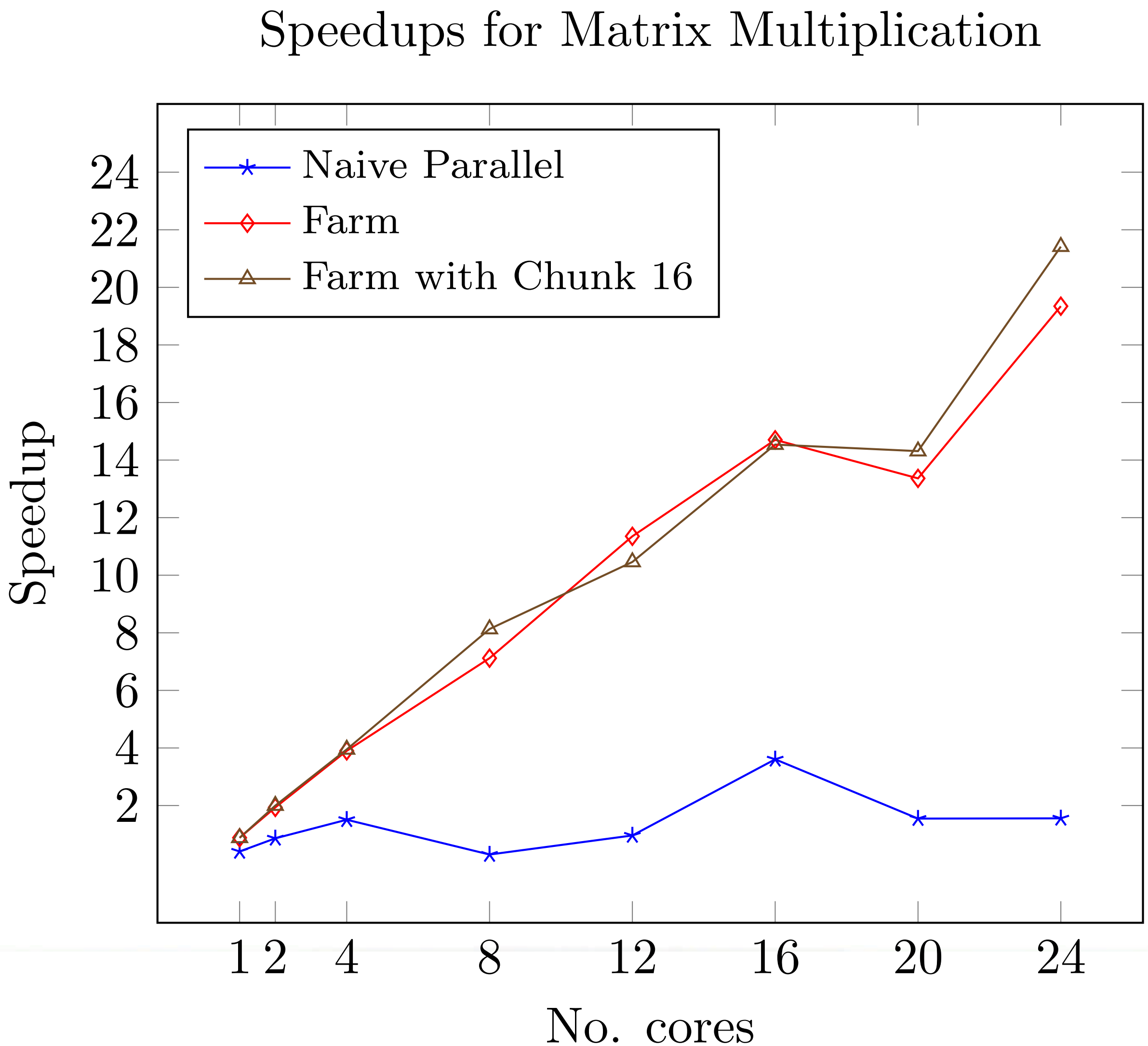
# Farm Skeleton

- Each worker is executed in parallel
- A bit like a 1-stage pipeline



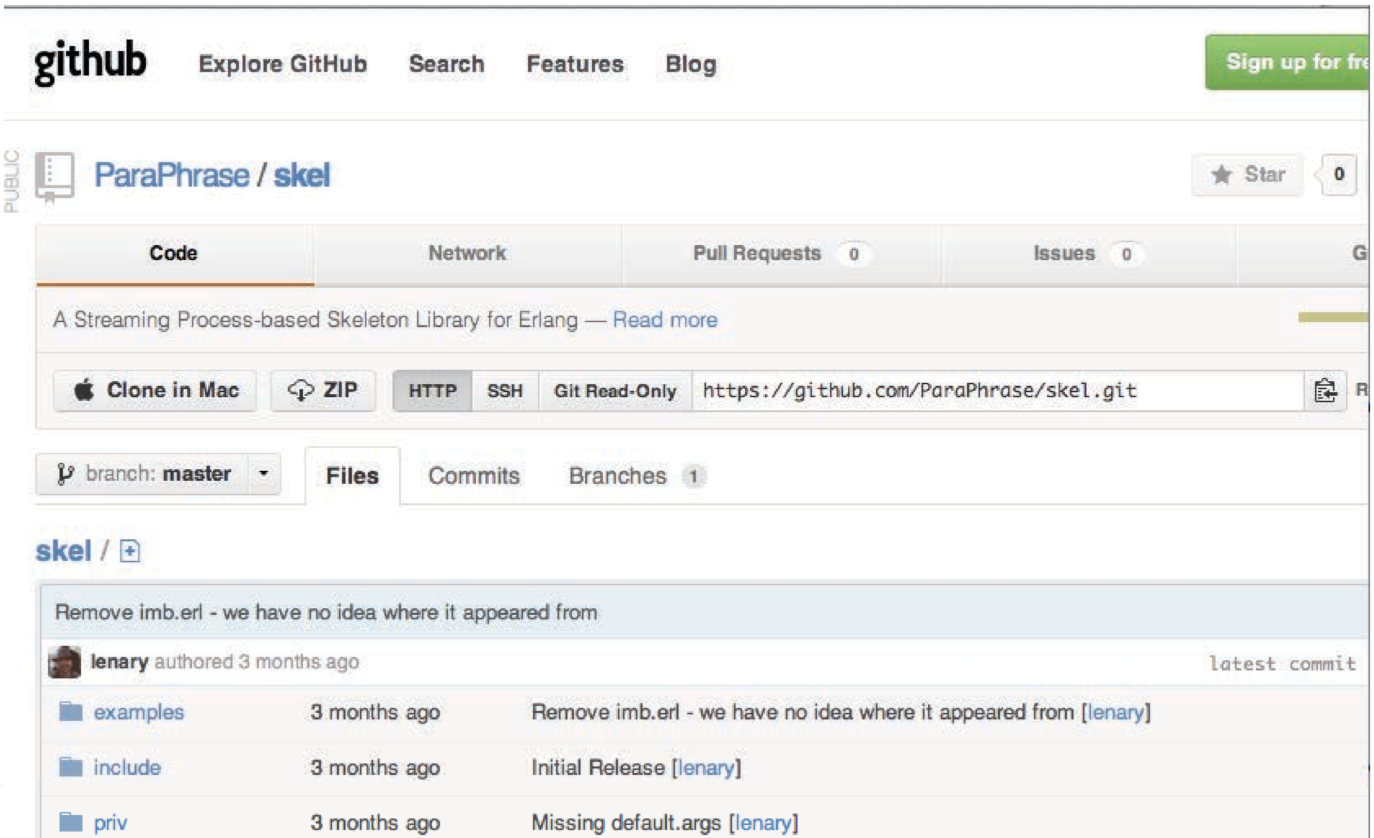

```
skel:do([{farm, Skel, M}], Inputs).
```

# Using The Right Pattern Matters



# Download from ...

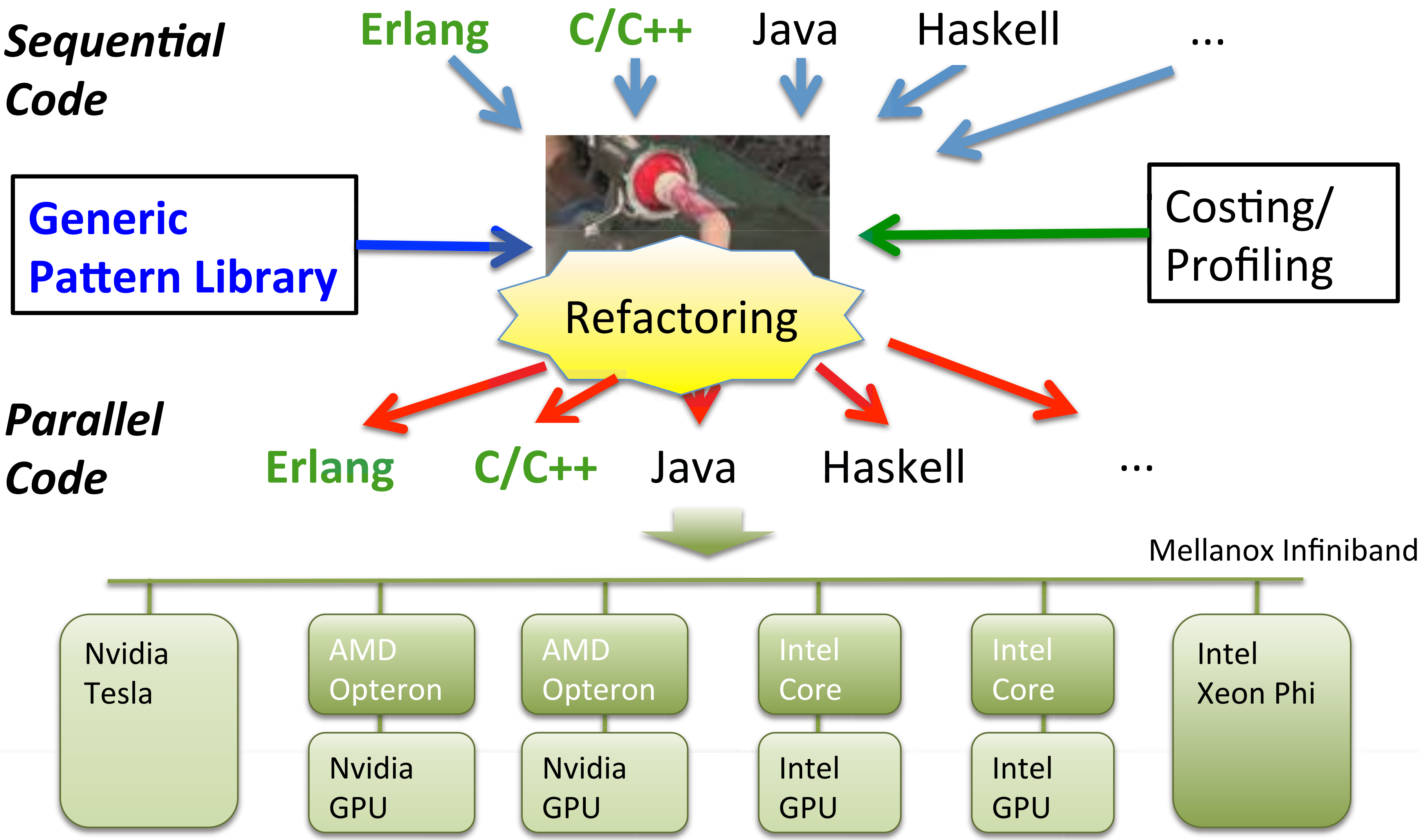
http://www.cs.st-andrews.ac.uk/~chrisb/ParaPhrase_Refactorer.tar.gz (Refactoring Tool)
https://github.com/ParaPhrase/skel (Skel Library)



# Constructing Farms…

- Seq, component wrapper for worker function:
  - `{seq, fun worker/1}`
- Create a farm of workers:
  - `{farm,[{seq, fun worker/1}], nWorkers}`
- Wrap it inside a skel call:
  - `skel:do([{farm, [{seq, fun worker/1}], nWorkers}], input)`

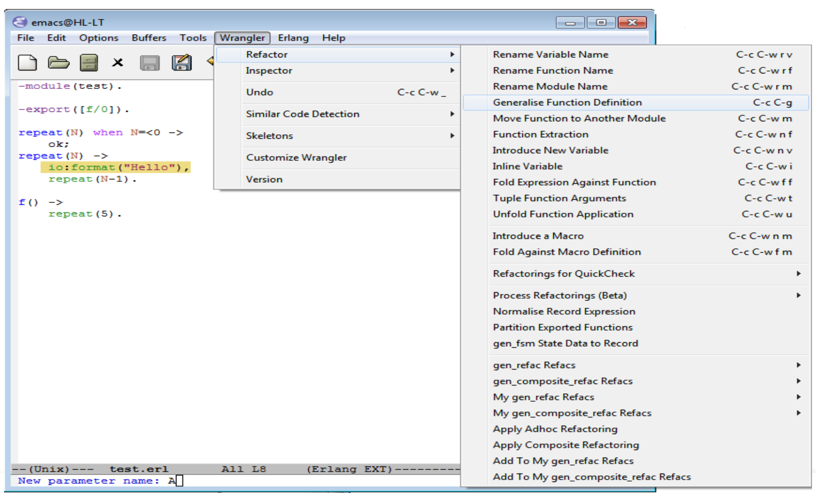
# The ParaPhrase Approach

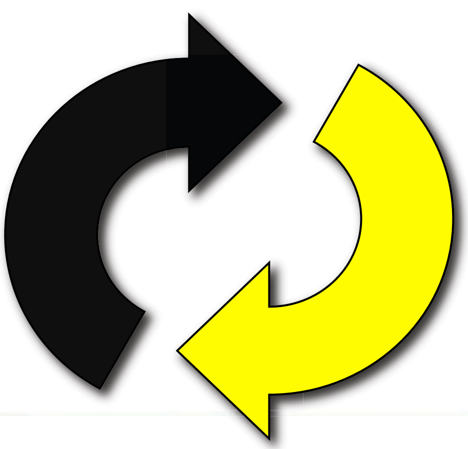


# Refactoring Tool Support

- The process of changing the structure of an application while preserving its functional semantics

- Semi-automated approach that is more general than fully automated parallelisation techniques



# Programing Heterogeneous Systems…

- …is hard!
- Mainstream programming models (e.g. OpenCL, CUDA+pthreads) are too low-level for an average programmer
- Many applications can be parallelised in more than one way
- Choosing which parallel structure to exploit is a non-trivial problem
  - Trial-and-error approach can be very costly

# Linking with OpenCL

- OpenCL binding for Erlang
  - Basically wraps up openCL in Erlang ‘FFI’ like calls
  - User required to provide an openCL kernel
  - Provides GPU setup/offloading/marshalling …
  - Requires kernel parameters to be Erlang binaries
    - Basically a pointer to the raw data
  - https://github.com/tonyrog/cl

# Linking with OpenCL

```
E = clu:setup(all),
{ok,Program} = clu:build_source(E, "solve2"),
{ok,Kernel} = cl:create_kernel(Program,
                               "solveKernel”)

cl:create_buffer(E#cl.context, [read_only],
                    byte_size(Argument)),

cl:set_kernel_arg(Kernel, 0,
                         K#kwork.argument),
```

# Linking with OpenCL

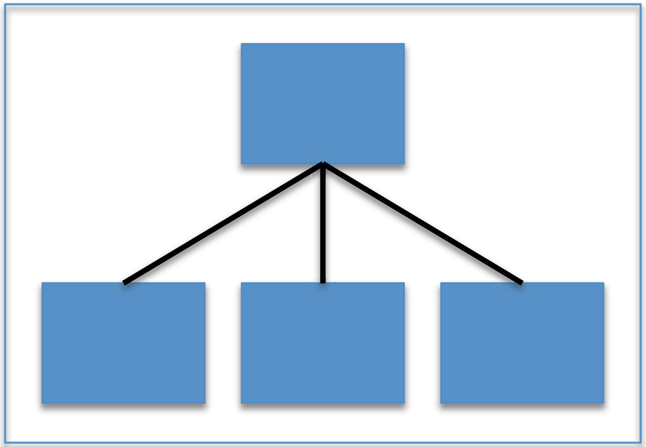
```
{ok,E3} =
cl:enqueue_read_buffer(K#kwork.queue,

                    K#kwork.omem,0,Nk,[E2]),

{ok,Bin} = cl:wait(K#kwork.e3),
```

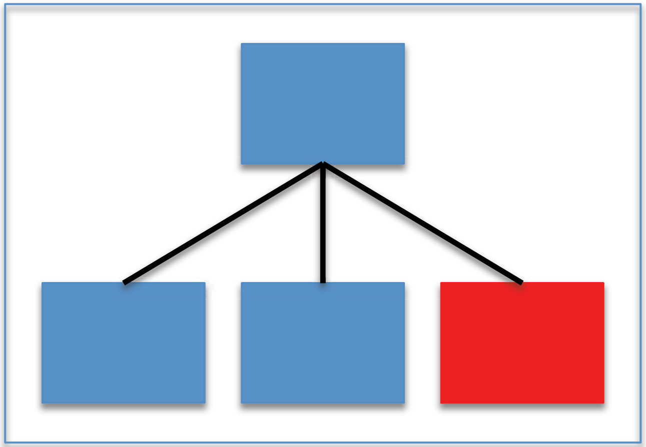
# Heterogeneous Patterns

Farm



# Heterogeneous Patterns

Heterogeneous
Farm



# Heterogeneous Farms

- New types of heterogeneous components:
  - {seqCPU,  fun CPUworker/1, nCPUWorkers}
  - {seqGPU, fun GPUworker/1, nGPUWorkers}
- Heterogeneous Farms:
  - Skel:do([{farm, {seqCPU, fun CPUworker/1, nCPUWorkers},
    {seqGPU, fun GPUworker/1, nGPUWorkers}], inputs)

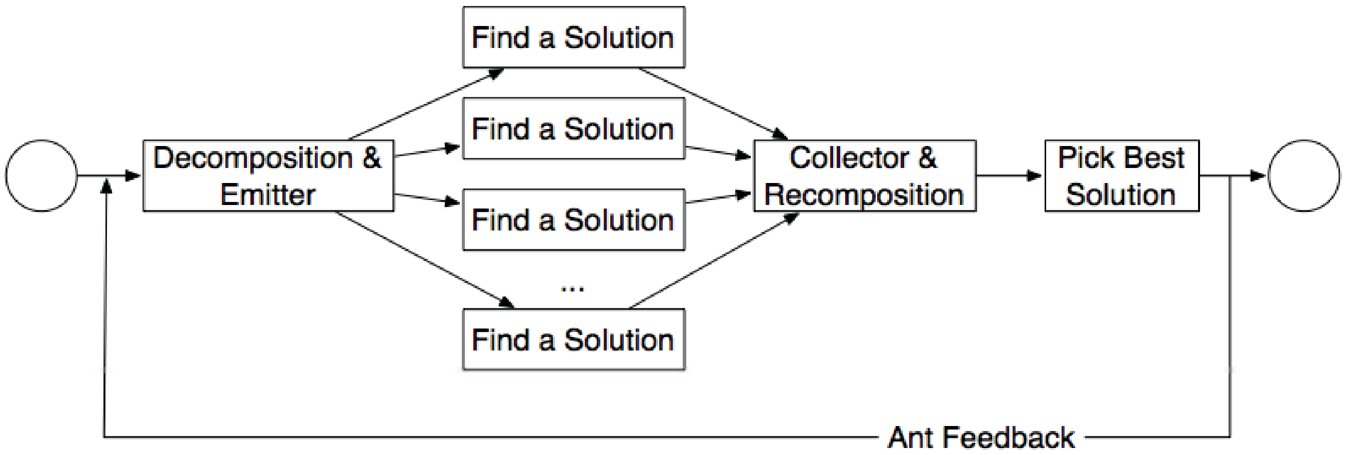
# Heterogeneous Parallel Refactoring

- Generates calls to openCL bindings
  - Uses dialyzer underneath to find the types of the kernel arguments
- Eliminates tedious and massively error-prone openCL writing
- Assumes an already supplied openCL kernel
- Adds in number GPU/CPU workers, using a static mapping technology

# Ant Colony Optimisation



- An ACO algorithm consists of a number of iterations in which each ant finds a solution, partially guided by a *pheromone trail.*
- The *pheromone trail* is updated based on the best solution in each iteration.
- We use ACO to solve the Single Machine Total Weighted Tardiness Problem
- A Skel task farm and feedback skeletons are used to parallelise ACO



# Ant Colony Optimisation

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```
ant_colony(FName, Num_Ants, Num_Iters, Num_Workers) ->
   {Num_Jobs, Process_Time, Weight, Deadline, Tau} =
binary_ant_init:init(FName),
   Chunk_Size = Num_Ants div Num_Workers,

   Pipe = {pipe, [{farm, [{seqCPU, fun(X) -> lists:map(fun(Y) ->
                         binary_par_solve:find_solution(Y) end, X) end,
                         nCPUWorkers}],

             {seq, fun(X) -> pick_update_spawn_list_lists(Num_Workers,
                                              Chunk_Size, X) end}]},
```

# Ant Colony Optimisation

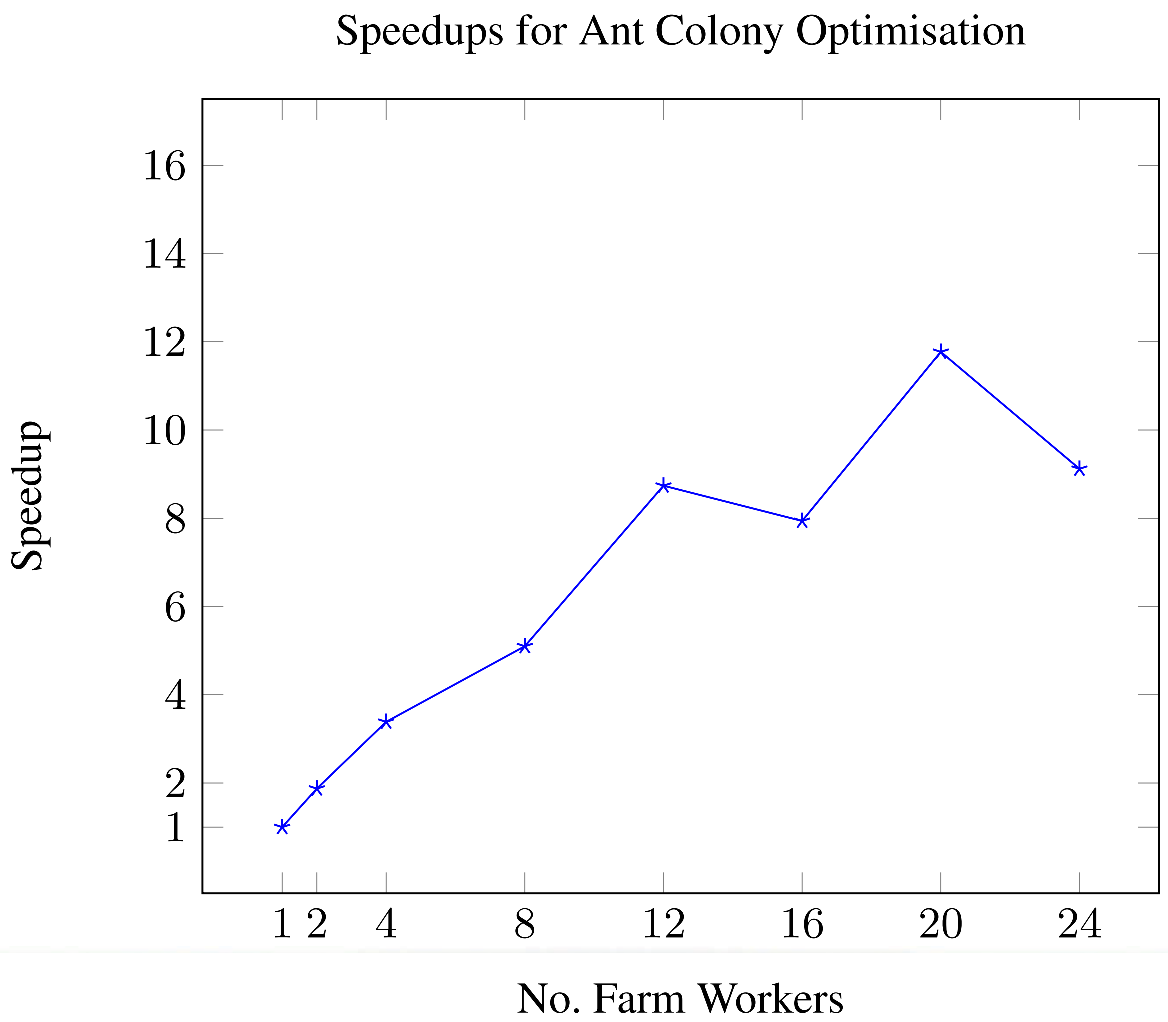
```
Feedback = {feedback, [Pipe], fun ant_feedback/1},
   skel:do([Feedback], [lists:duplicate(Num_Workers,
                        lists:duplicate(Chunk_Size,
                              {Num_Jobs, Process_Time, Weight,
Deadline, Tau, Num_Iters}))]).
```

# Experimental Machine

All measurements

- 2.4GHz 24-core, dual AMD Opteron 6176 architecture
- Nvidia Tesla C2050 Fermi GPU (448 CUDA cores)
- Centos Linux 2.6.18-274.e15.
- Erlang 5.9.1 R15B01,
- Averaging over 10 runs

# Parallel ACO with Skel



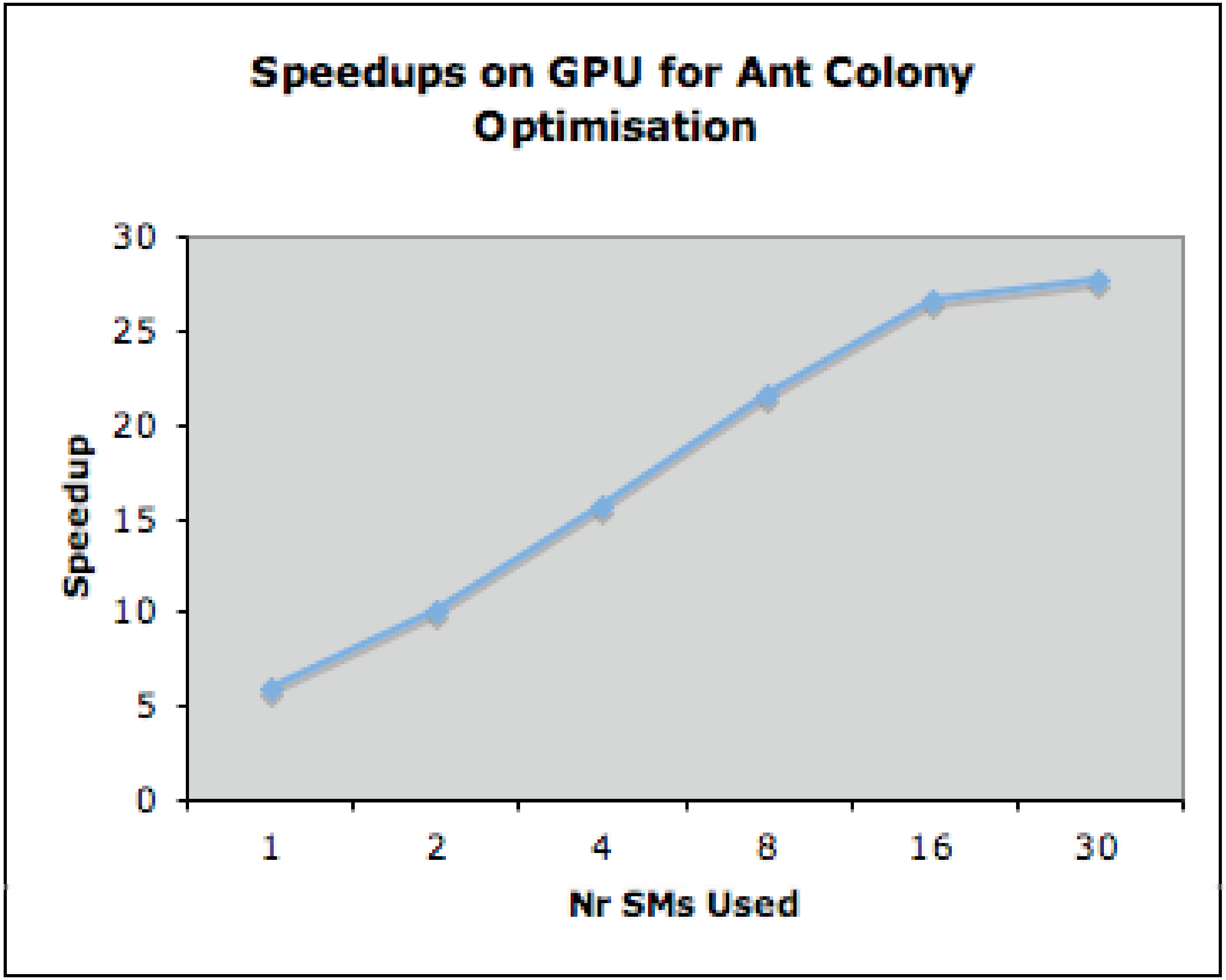
# GPU ACO, Refactored

```
Pipe = {pipe, [{farm, [{seqGPU, fun(X) -> lists:map(fun(Y) ->
                          binary_gpu_solve:find_solution(Y) end, X) end,
                          nGPUWorkers}],

          {seq, fun(X) -> pick_update_spawn_list_lists(Num_Workers,
                                                      Chunk_Size, X) end}]},
```

# GPU ACO, Refactored

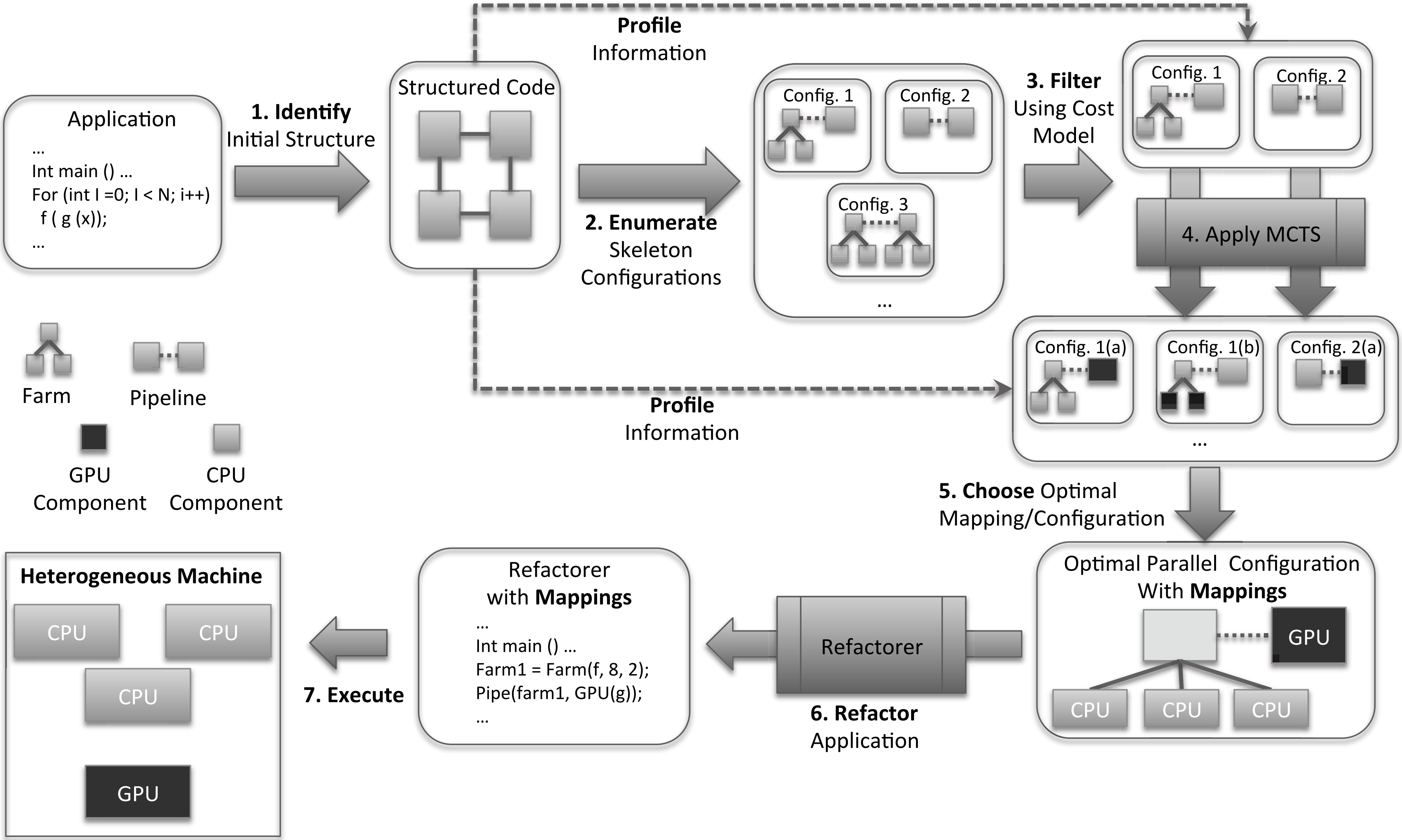
```
find_solution_gpu(...) ->
      E = clu:setup(all),
      {ok,Program} = clu:build_source(E, "solve2"),
      {ok,Kernel} = cl:create_kernel(Program, "solveKernel"),
      Random_Seed = 0,
      Tabus = list_to_tuple(lists:duplicate(Num_Jobs,1)),
Kws =
      map(
        fun(Device) ->
              {ok,Queue} = cl:create_queue(E#cl.context,Device,[]),
              {ok,Local} = cl:get_kernel_workgroup_info(Kernel,Device,
                                work_group_size),
              {ok,Freq} = ...
Kws3 = map(
          fun(K) ->
                {ok,ProcessTimeBuffer}  = cl:create_buffer(E#cl.context,[read_only],byte_size(Process_Time)),
 {ok,E1} = cl:enqueue_write_buffer(K#kwork.queue,
                                K#kwork.imem,
                                0, Nk,
                                K#kwork.idata, []),

ok = cl:set_kernel_arg(Kernel, 0, K#kwork.resultsBuffer),
            ...
                         Global = Count,
            {ok,E2} = cl:enqueue_nd_range_kernel(K#kwork.queue,
                                  Kernel,
                                  [Global], [K#kwork.local],
                                  [E1]),

                ...

                K#kwork { processTimeBuffer=ProcessTimeBuffer  ...  }
          end, Kws),
 Bs = map(
         fun(K) ->
               {ok,Bin} = cl:wait(K#kwork.e3),
               cl:release_mem_object(K#kwork.imem),
               cl:release_mem_object(K#kwork.omem),
               cl:release_queue(K#kwork.queue),
                          Bin
         end, Kws4),
```

# GPU Results

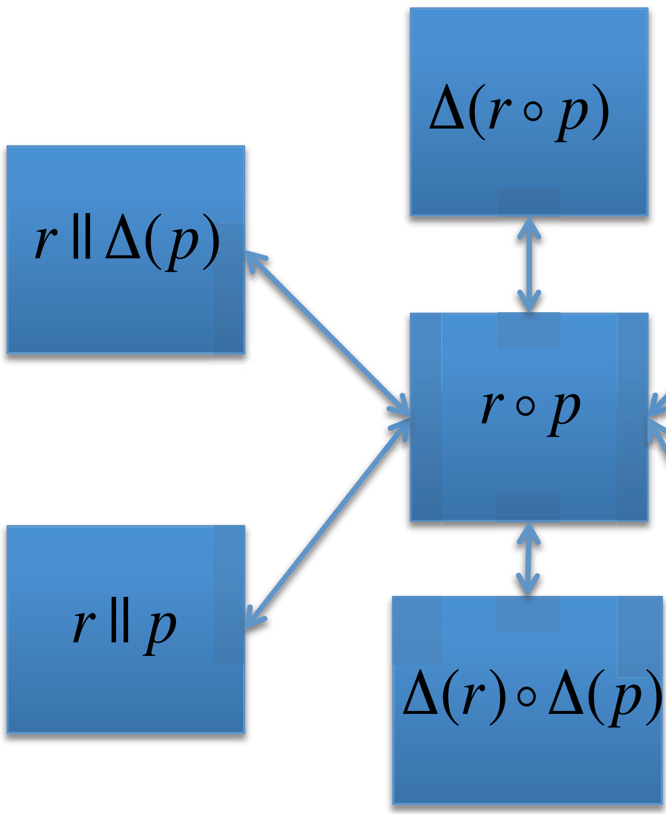


Speedups on GPU for Ant Colony Optimisation
Speedup
30
25
20
15
10
5
0
1
2
4
8
16
30
Nr SMs Used

# Heterogeneous Parallel Programming



# Example: Enumerate Skeleton Configurations for Image Convolution




| Configuration | Est. runtime |
|---|---|
| $r \circ p$ | 5.6 |
| $r \parallel p$ | 3.88 |
| $\mathbf{\Delta(r) \parallel p}$ | **1.60** |
| $r \parallel \Delta(p)$ | 4.00 |
| $\mathbf{\Delta(r) \parallel \Delta(p)}$ | **0.40** |
| $\mathbf{\Delta(r \parallel p)}$ | **0.56** |
| $\Delta(r) \circ \Delta(p)$ | 2.00 |
| $\Delta(r) \circ p$ | 2.00 |
| $r \circ \Delta(p)$ | 5.60 |

$r$ : read image file

$p$ : process image file

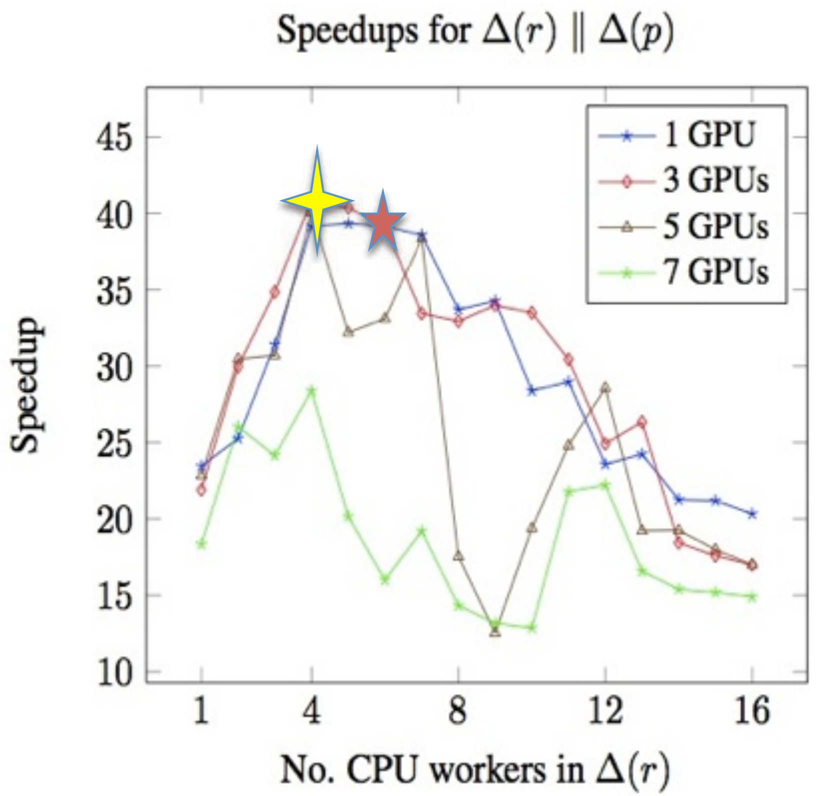
# Results on Benchmark: Image Convolution

MCTS Mapping (C, G):

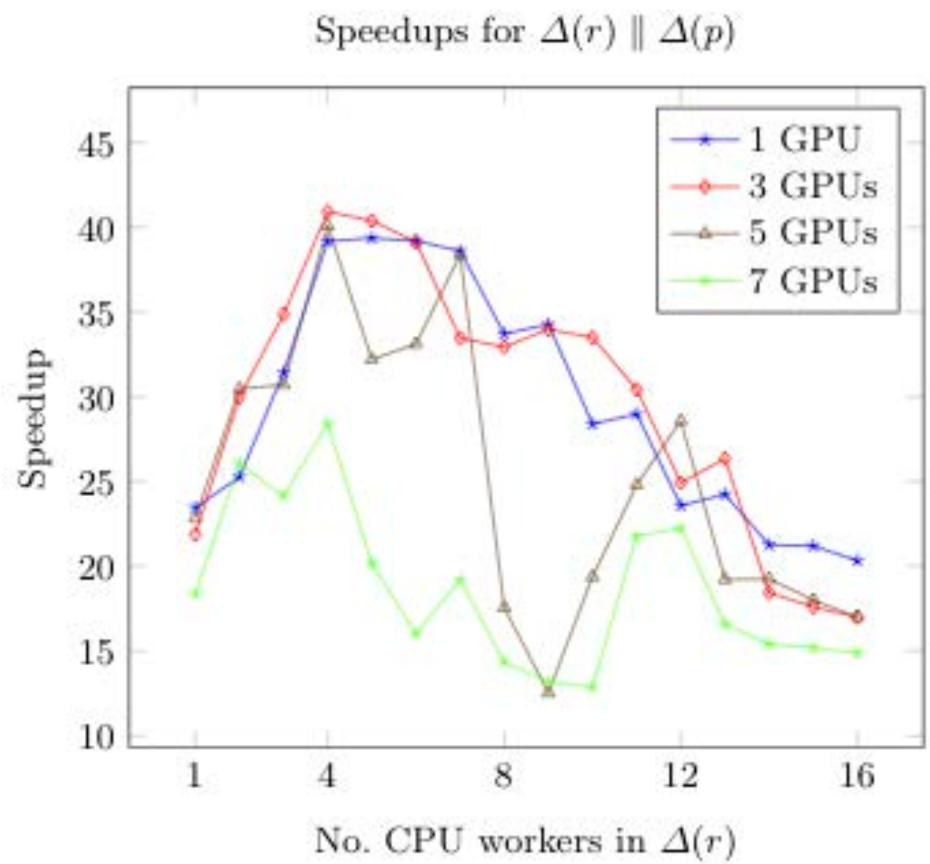
(6, 0) | | (0, 3)

**Speedup 39.12**

Best Speedup: 40.91



# Adding Mapping...




- The best speedup was predicted for $\Delta(r, 6, 0) \parallel \Delta(p, 0, 3)$

# Adding Mapping (2)

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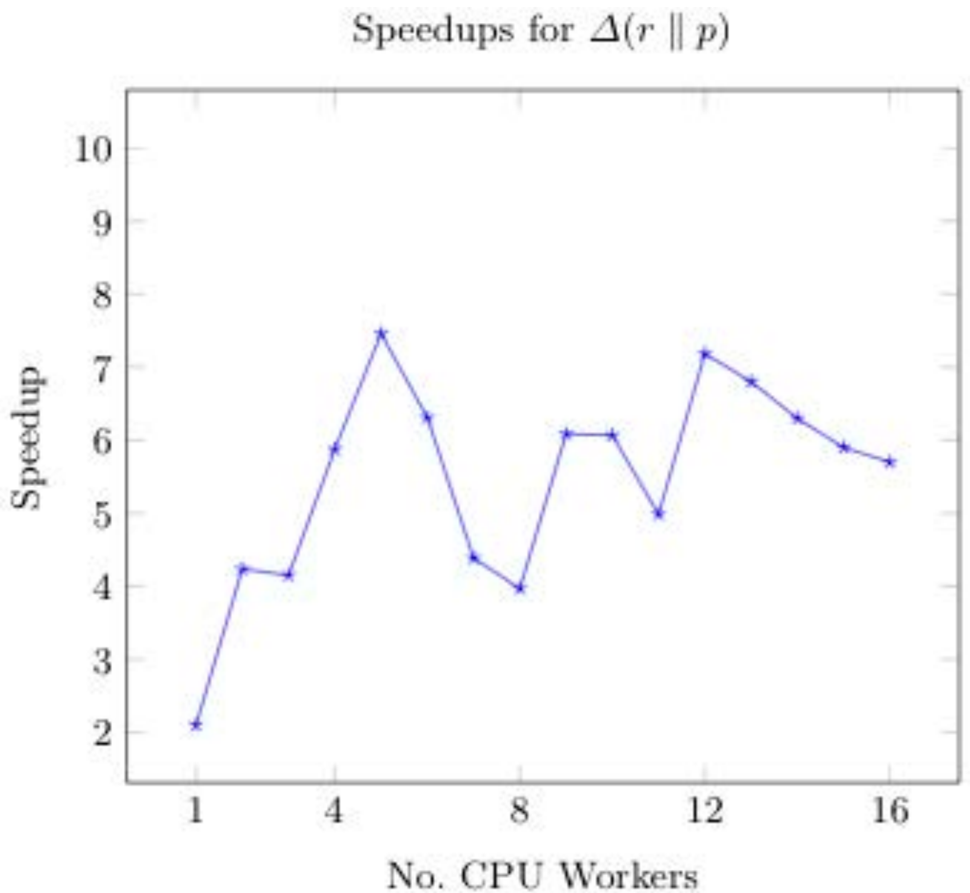
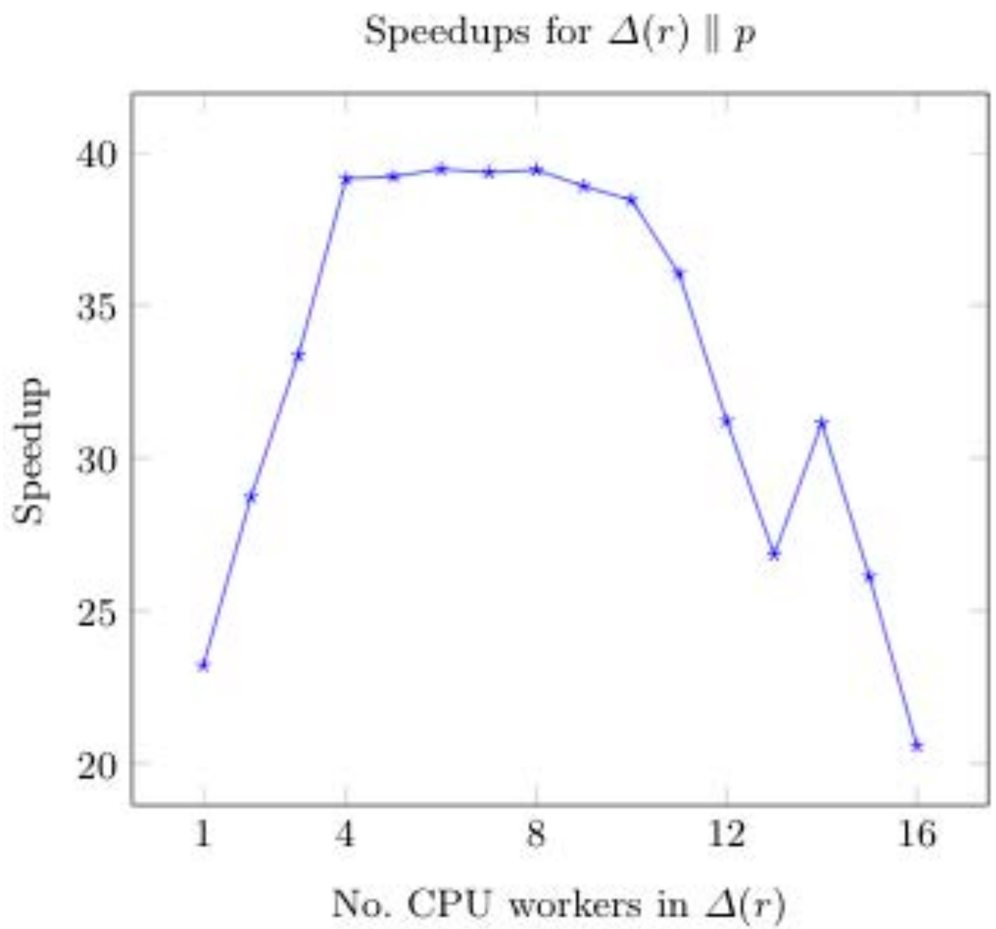



- The best speedup was predicted for $\Delta(r \parallel p, 5, 5)$

# Adding Mapping (3)




- The best speedup was predicted for $\Delta(r, 4, 0) \parallel p_G$

# Conclusions

- New heterogeneous skeletons for Erlang
- New Heterogeneous refactoring approach, semi-automatically introduces openCL bindings, and skeletal configuration
- Initial results for an ant colony optimisation
  - Skeletal, farm with feedback version, 12 speedup
  - GPU version, 26 speedup

# Conclusions

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- The manycore revolution is upon us
  - Computer hardware is changing very rapidly (more than in the last 50 years)
  - The **megacore** era is here (aka exascale, BIG data)
- Heterogeneity and energy are both important
- Most programming models are too low-level
  - concurrency based
  - need to expose mass parallelism
- Patterns and *functional programming* help with abstraction
  - millions of threads, easily controlled

# Conclusions (2)

- Functional programming makes it easy to introduce parallelism
  - (Controlled) side effects means any computation could be parallel
  - Matches pattern-based parallelism
  - Much detail can be abstracted
- Lots of problems can be avoided
  - e.g. Freedom from Deadlock
  - Parallel programs give the same results as sequential ones!
- Automation is very important
  - Refactoring dramatically reduces development time
    (while keeping the programmer in the loop)
  - Machine learning is very promising for determining complex performance settings

# Future Work

- Allow further integration into skeletons
  - A living mixture of CPU/GPU components
- Wider range of skeletons
  - Parallel workpools
  - Divide-and-conquer
  - Map-reduce
  - BSP
- More case studies, and from different domains:
  - Physics, computer algebra, …
- Include dynamic remapping and distributed computing environments

# Funded by

- **ParaPhrase (EU FP7), Patterns for heterogeneous multicore,**
  €4.2M, 2011-2014
- **SCIEnce (EU FP6), Grid/Cloud/Multicore coordination**
  - €3.2M, 2005-2012
- **Advance (EU FP7), Multicore streaming**
  - €2.7M, 2010-2013
- **HPC-GAP (EPSRC), Legacy system on thousands of cores**
  - £1.6M, 2010-2014
- **Islay (EPSRC), Real-time FPGA streaming implementation**
  - £1.4M, 2008-2011
- **TACLE: European Cost Action on Timing Analysis**
  - €300K, 2012-2015

# Some of our Industrial Connections

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