GPU TECHNOLOGY CONFERENCE
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The Brightest People
The Best Ideas
The Biggest Opportunities

FastFlow: Combining Pattern-Level Abstraction and Efficiency in GPGPUs

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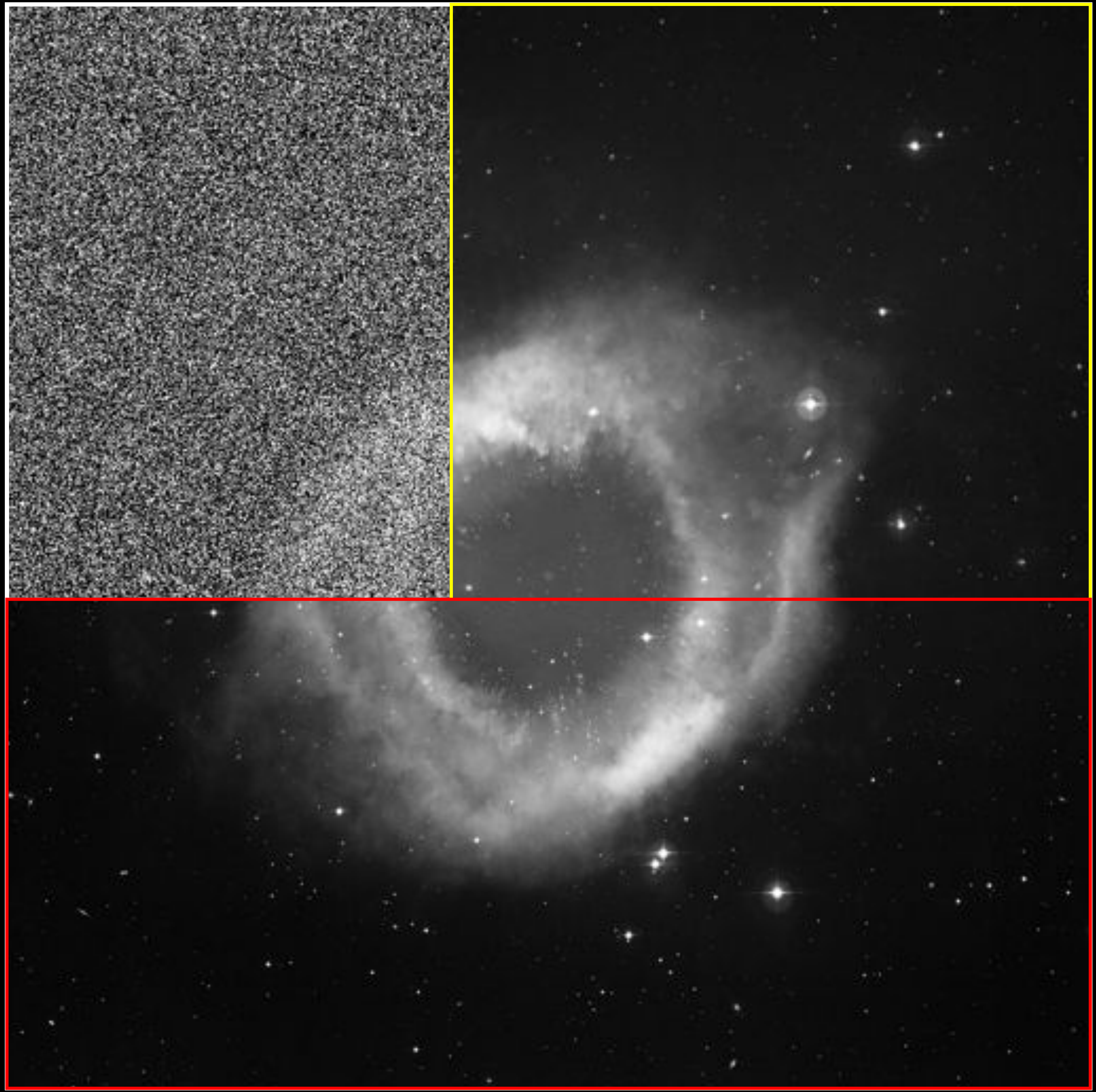
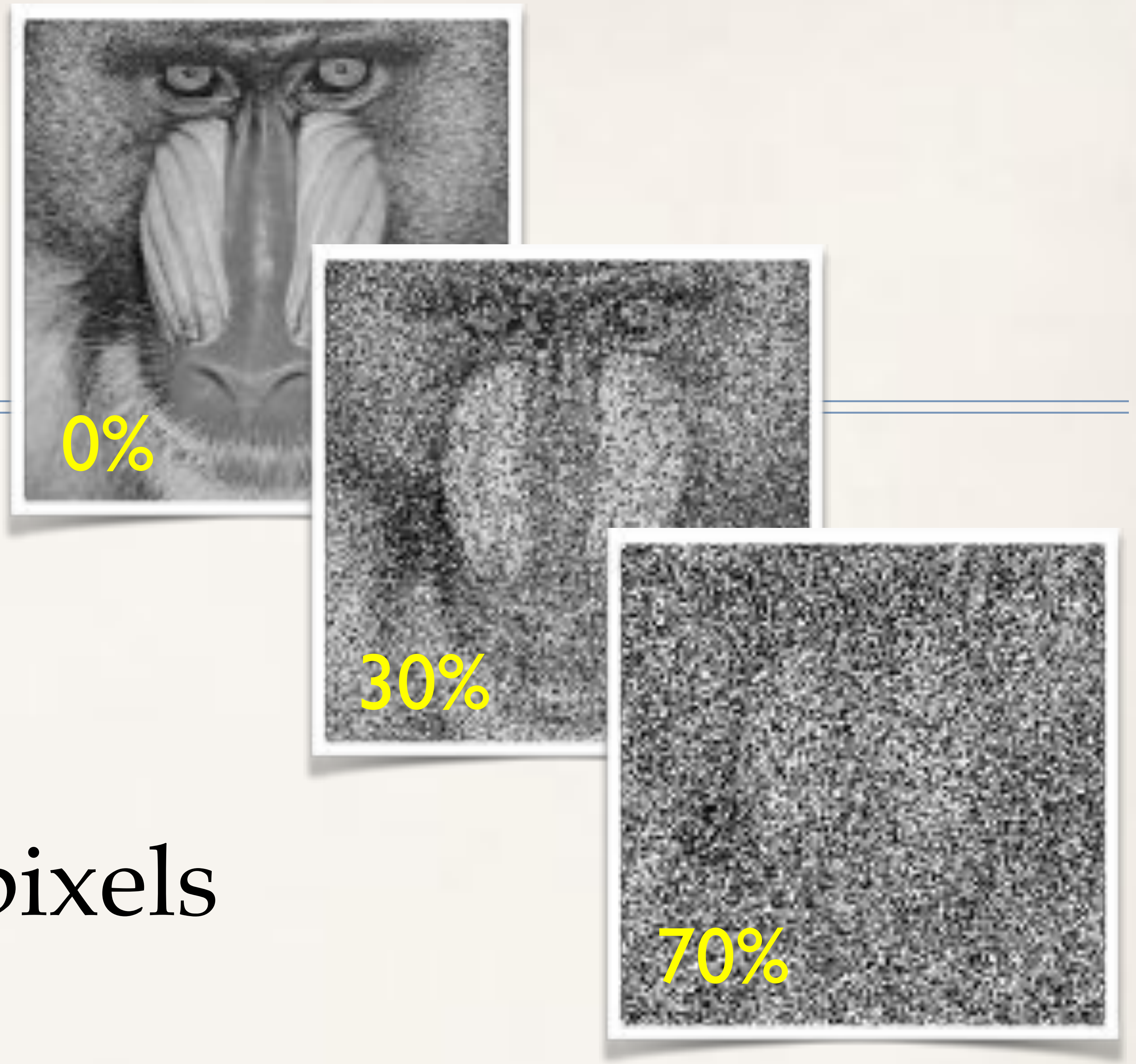
Outline

- Motivational example
  - An effective (and quite universal) image/video denoiser
  - Paradigmatic programming pattern for GPGPUs?
- On patterns for multicore and GPGPUs
  - FastFlow
  - Some performance results
  - A demo


Salt&Pepper
noise 70%
Restored
Original

Salt & Pepper noise



- Electronic and signal noise
- Uniform distribution of "saturated" white/black pixels
  - Measured as percentage of affected vs overall pixels
- Typically restored using statistic filters: e.g. median, median-adaptive
- Not satisfactory for high levels of noise
  - not only outliers are filtered (image results smoothed)

Salt & Pepper noise

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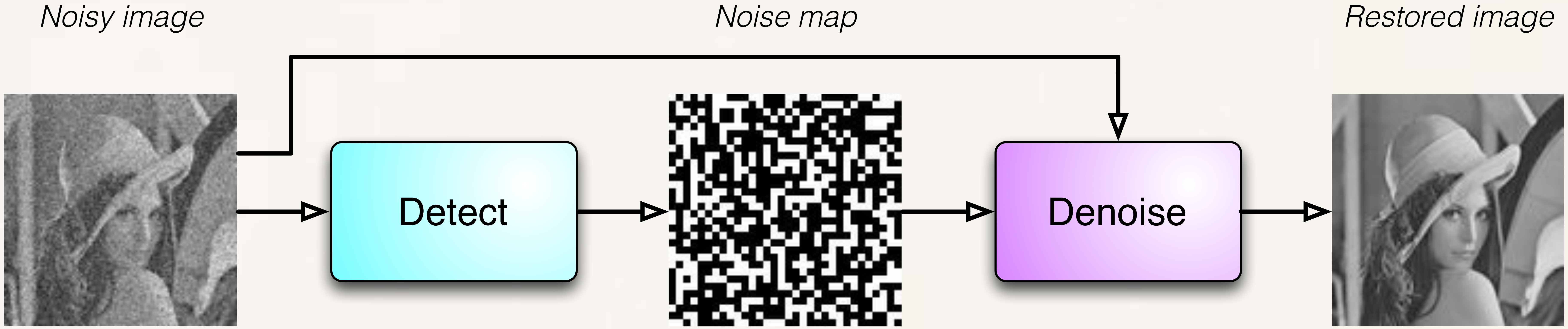
Gaussian noise

Original
Var 10
Var 30
Var 50

- Poor illumination, temperature, circuit noise
- White additive noise in the frequency domain
  - Measured with mean and variance of the Gaussian distribution
  - Affect all pixels, with an additive “white” value distributed as a Gaussian
- Typically restored using statistic filters: e.g. median, Guassian smoothing
- More difficult to manage: restored image results smoothed

Two-stage restoring

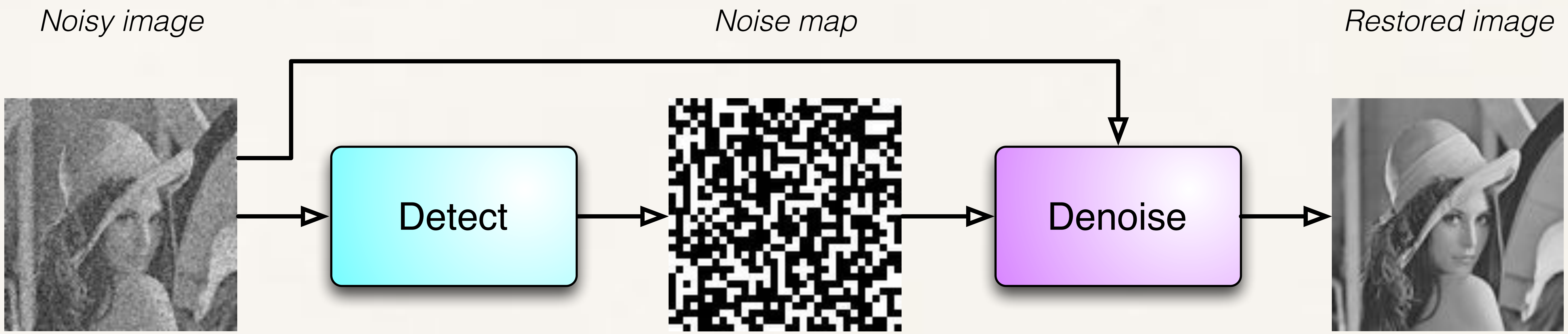


- progressive-switching/adaptive median
- neural/bayesian networks, fuzzy, …

- variational
- statistic

- Decouple detection decoupled from restoration
  - Pixels considered not outliers are not altered by restoration
  - False positives impair restoration quality

Two-stage restoring



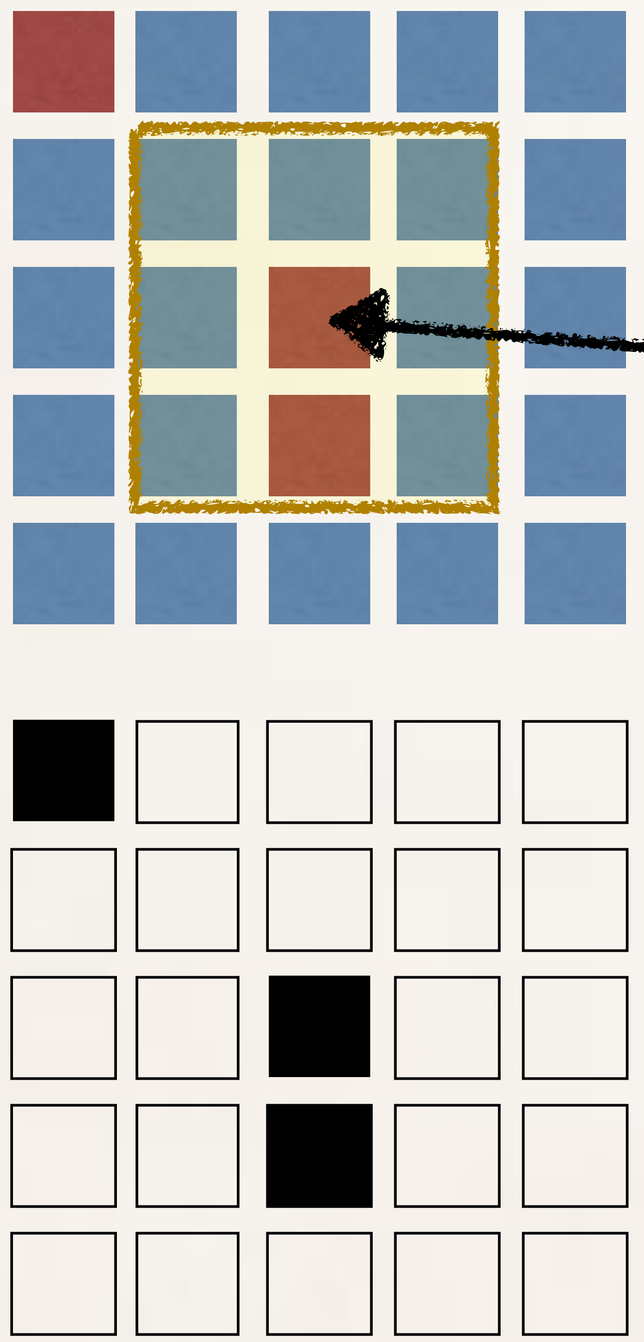
- **progressive-switching/adaptive median**
- neural/bayesian networks, fuzzy, …

- **variational**
- statistic

- Statistic detection + variational restoration
  - High quality, edge-preserving filtering
  - Much more computational demanding, not really viable without parallelism
    - Matlab on a single 256x256 image with 50% of noise requires dozen of minutes
  - Stages can be pipelined

Variational De-noising: an iterative optimisation problem

img



noiseMap

*Try any possible color **k** for the pixel, choose **u**, the one that minimize the value of F(neighb8(i,j))*

F(…) weight differently noisy and not noisy pixels

```
do
  foreach i,j
    if (noisyMap[i,j])
      let N = neighb8(img,i,j)
      let k in 0..255
        u=argmin(F(k,N,noiseMap))
      img[i,j]=u
while (process not converge)
```

You can write it directly with C++ and CUDA but what happens splitting the work onto 2 GPGPUs?

Variational Denoise: F(…) details (almost universal for different noise types)

regularization term data fidelity term

$$\operatorname*{argmin}_{u \in N} F(u) = \alpha \int R(u) + \beta \int D(u,d)$$

In the spatial domain

$$F_d|_N(u) = \sum_{(i,j)\in N} \left[|u_{i,j} - d_{i,j}| + \frac{\beta}{2}(S_1 + S_2) \right]$$

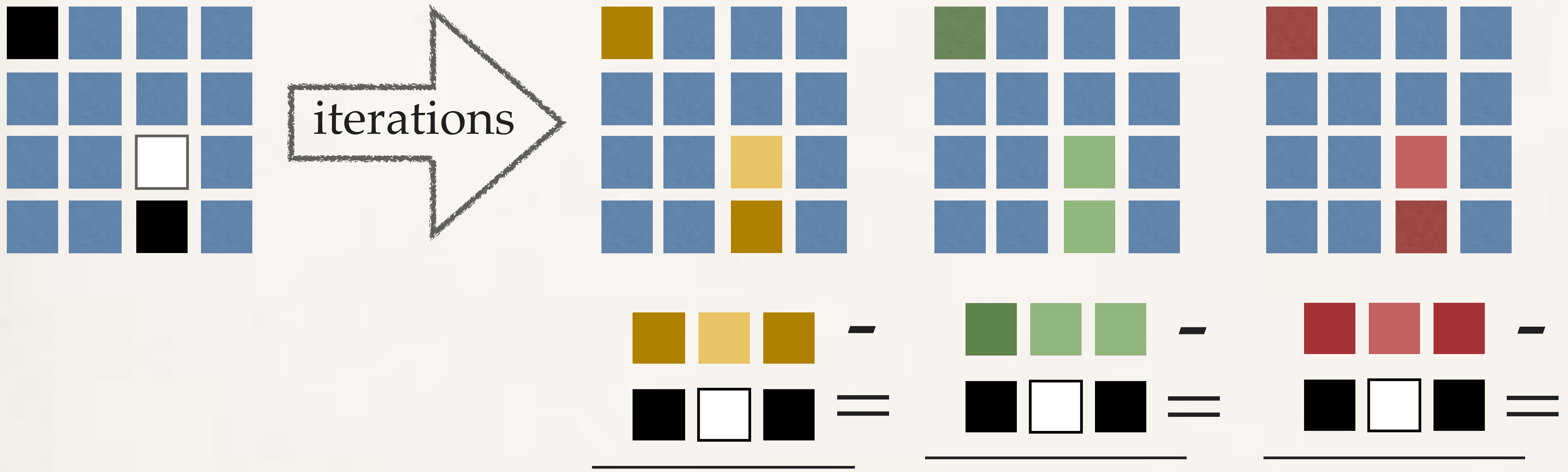
$$S_1 = \sum_{(m,n)\in V_{i,j}\cap N} 2 \cdot \varphi(u_{i,j} - d_{m,n}) \qquad S_2 = \sum_{(m,n)\in V_{i,j}\cap N^c} \varphi(u_{i,j} - u_{m,n})$$

$\varphi(t) = |t|^\alpha$ with $1 < \alpha \leq 2$ for Salt&Pepper

- R. Chan, C. Ho, and M. Nikolova, Salt-and-pepper noise removal by median-type noise detectors and detail-preserving regularization. IEEE Trans. on Image Processing, vol. 14, 2005.
- M. Aldinucci et al. A parallel edge preserving algorithm for salt and pepper image denoising. In Intl. Conference on Image Processing Theory Tools and Applications (IPTA), 2012. IEEE.

Convergence can't be evaluated with a reduce (involves three iterations, i.e. memory)

Noisy Img · Img (k-1) · Img (k) · Img (k+1)

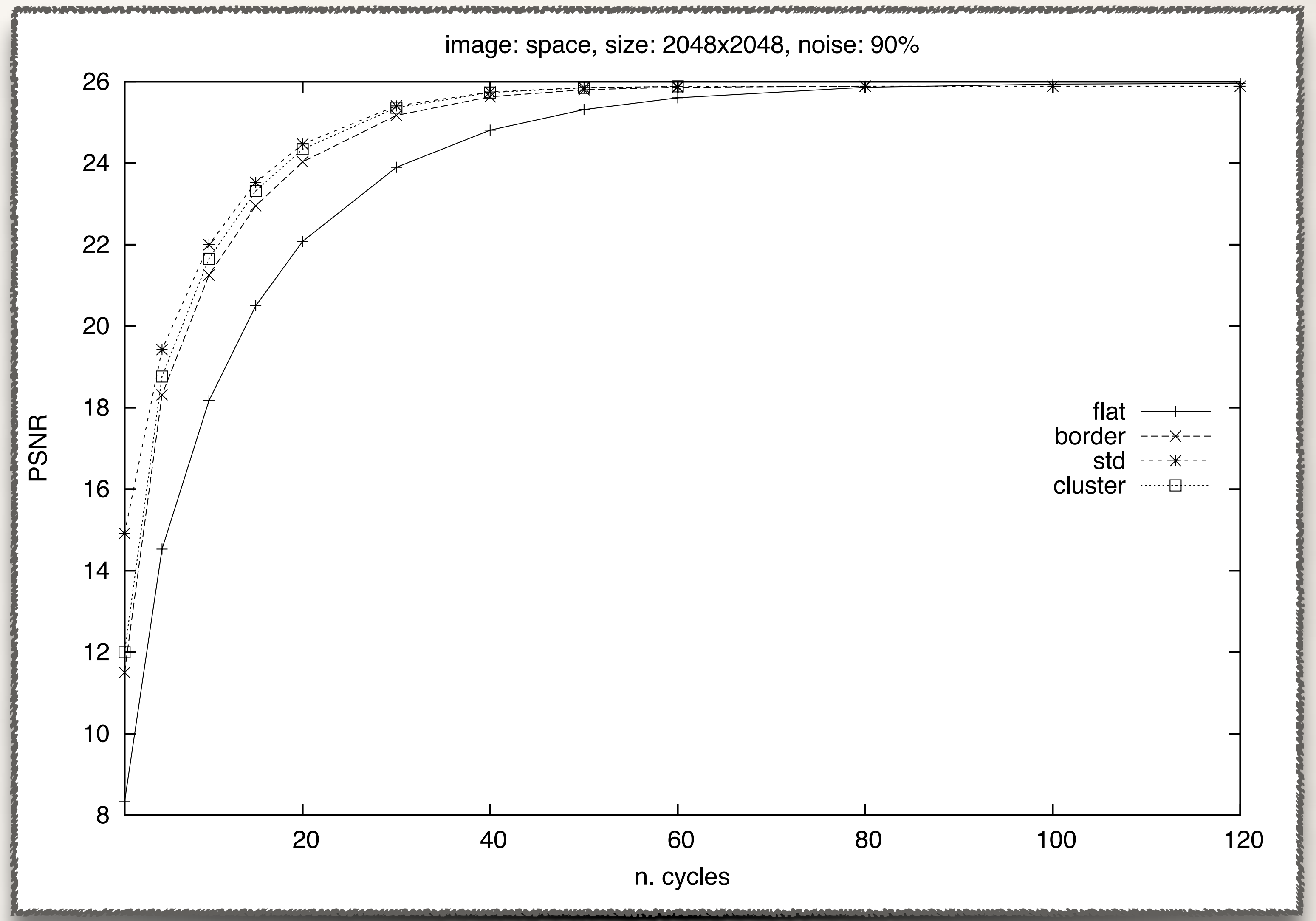


Residuals: 2 4 2 · 5 8 5 · 6 7 6

2 4 2 · 5 8 5

Diff of residuals: 3 4 3 · 1 1 1

Reduce of diffs: $\sum \Delta^{(k)} = 10$ · $\sum \Delta^{(k+1)} = 3$



quality →

time →

terminate if

$$\frac{\left|\left|\sum \Delta^{(k)}\right|\right| - \left|\sum \Delta^{(k+1)}\right|}{\left|\sum \Delta^{(k)}\right|} < \epsilon \in \mathcal{R}$$

M. Aldinucci, M. Drocco et al.
IJHPCA submitted

Quality results




Original
Baboon standard
test image
1024x1024

10% impulsive noise

50% impulsive noise

90% impulsive noise

Restored



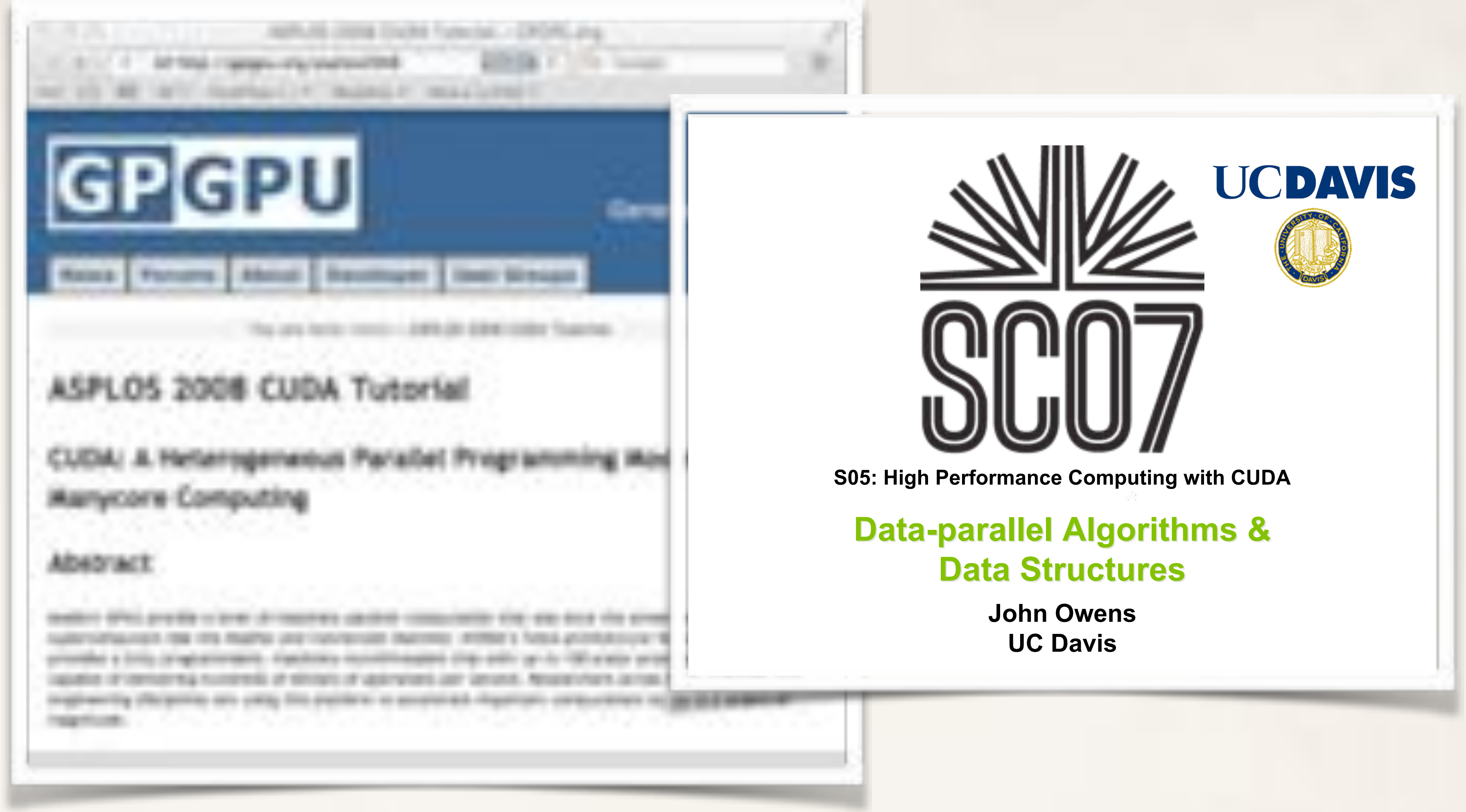
PNSR 43.29dB MAE 0.35

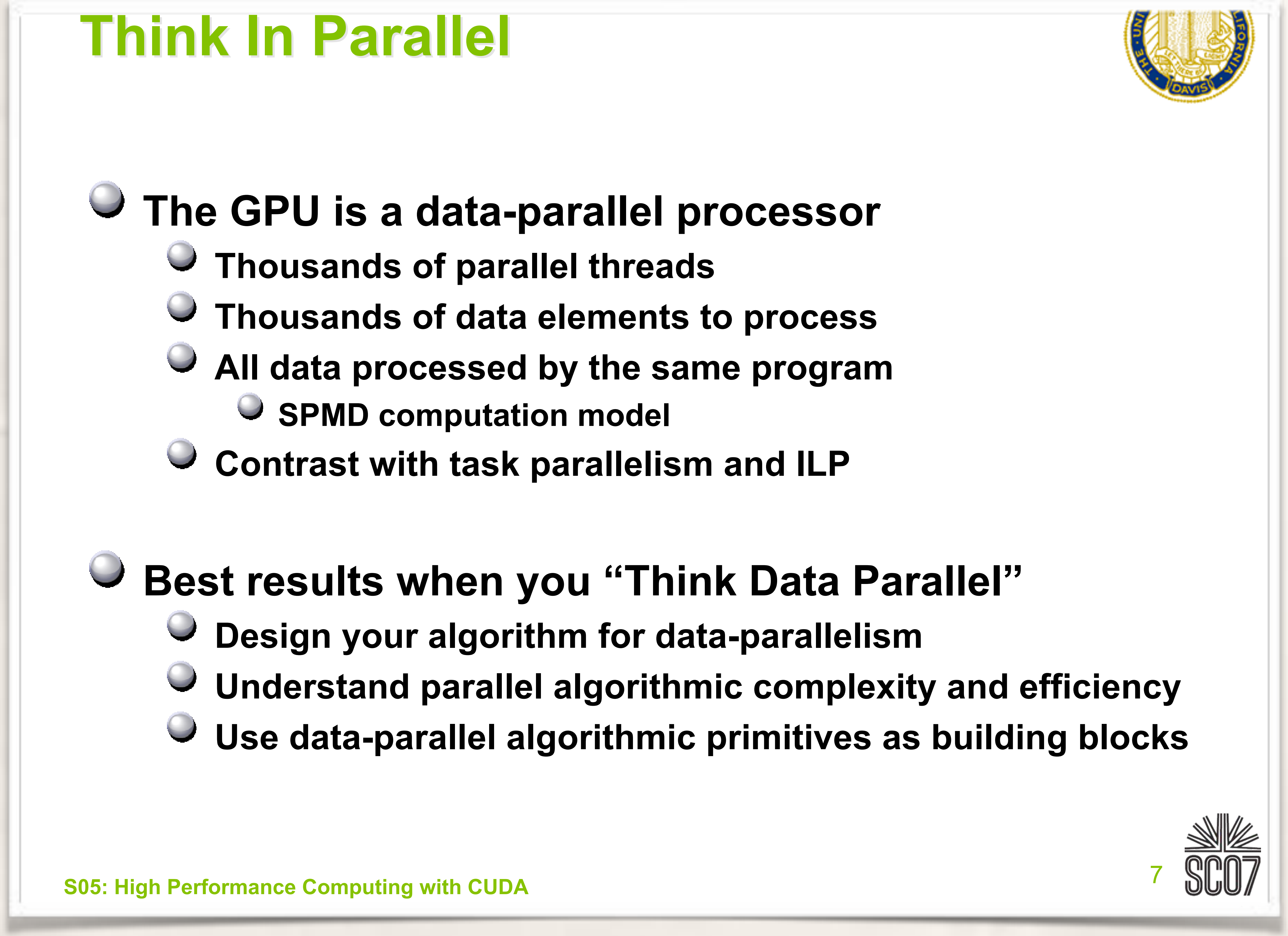
PNSR 32.75dB MAE 2.67

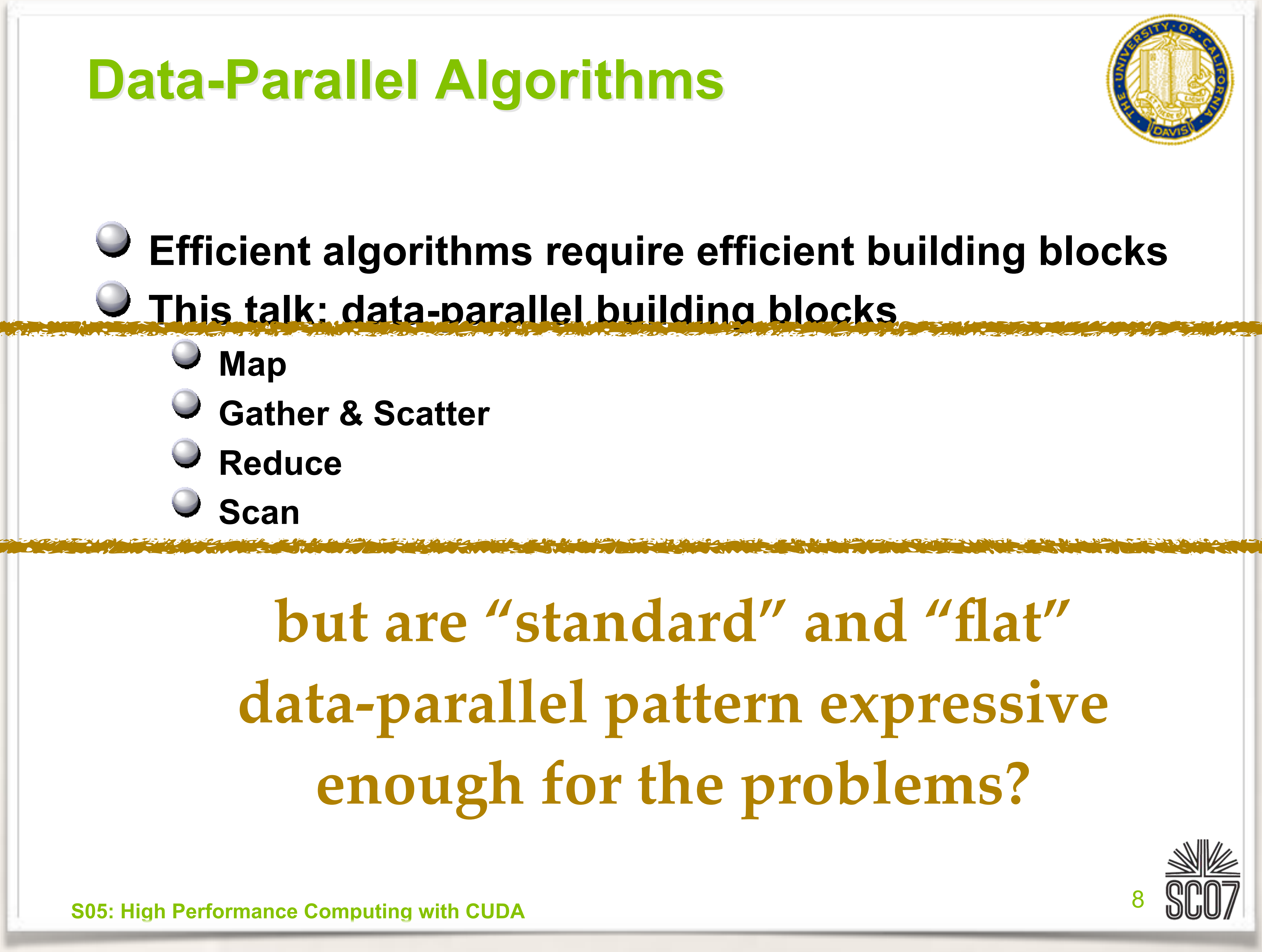
PNSR 23.4 MAE 11.21

Patterns are a natural approach in GPGPUs

… and this well-known from long time







but are "standard" and "flat" data-parallel pattern expressive enough for the problems?

Rationale: patterns are there but are not simply map or reduce

- Detect-Denoise can be naturally pipelined
- Denoise is a (sort of) map with a stencil
  - Where, x = < x1, x2, …, xn >, map f x = < f(x1), f(x2), …, f(xn) >
  - Can be written as a map, but is neither natural nor easy
- Convergence evaluation is map across three iterations and reduce
  - Even more complex to write it as a MapReduce (if not impossible)
- Cholesky LU or C4.5 tree pruning with map, reduce or MapReduce?

stencilReduce

- a (low-level) powerful pattern
- it capture most of the interesting data parallel GPGPUs computations
- Subsumes: map, reduce, mapReduce
- Programmers do not need to write any line of host code to drive the GPGPU
  - D2H/H2D, data feeding, synchronisations, block configurations, …

```
loop
   before (…)
   stencil<stencilK,reduceK> (data[i], env)
   reduce op data
   after (…)
```

stencilReduce

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Compute on host
possibly in parallel on CPU cores

Unified Memory
greatly simplify this part

```
loop
    before (…)
    stencil<stencilK,reduceK> (data[i], env)
    reduce op data
    after (…)
```

CUDA code

Compute on host
possibly in parallel on CPU cores

Low-level approaches = lot of freedom (threads, CUDA, OpenCL, MPI, …)

you can design your algorithms as you want

… as a car, you can drive it where you want

car

Val D'Orcia, Tuscany, Italy

Low-level approaches = lot of freedom (threads, CUDA, OpenCL, MPI, …)

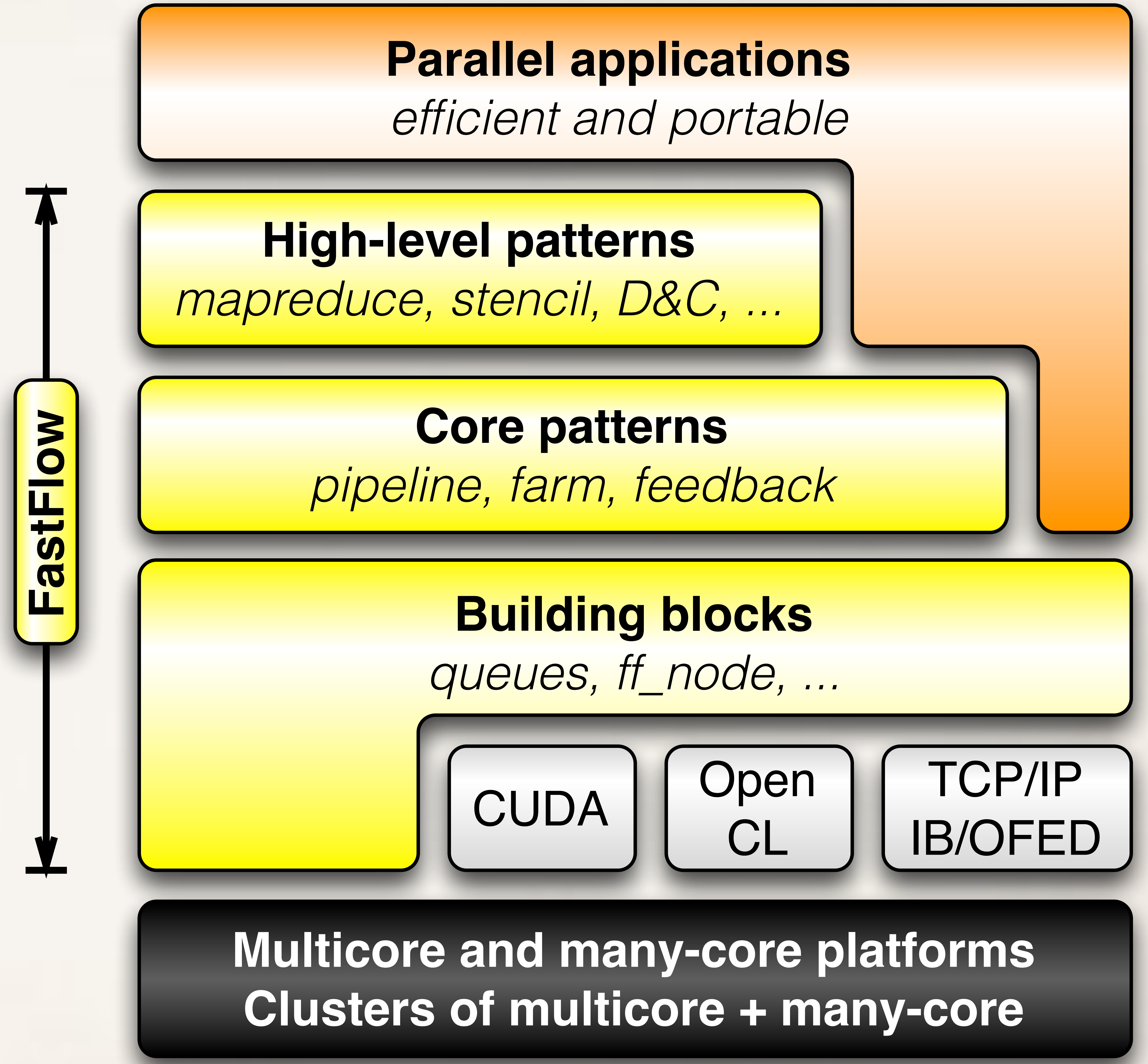
- Think in parallel & high-level
  - Efficiency, portability, time-to-market
- High-level parallel patterns
  - Describing collective behavior
  - Can be: expressive, efficient, compositional
  - Targeting multicore, GPGPUs, distributed with an unifying vision
  - On various CPUs/GPGPUs and OSes

you can design your algorithms as you want
… as a car, you can drive it where you want

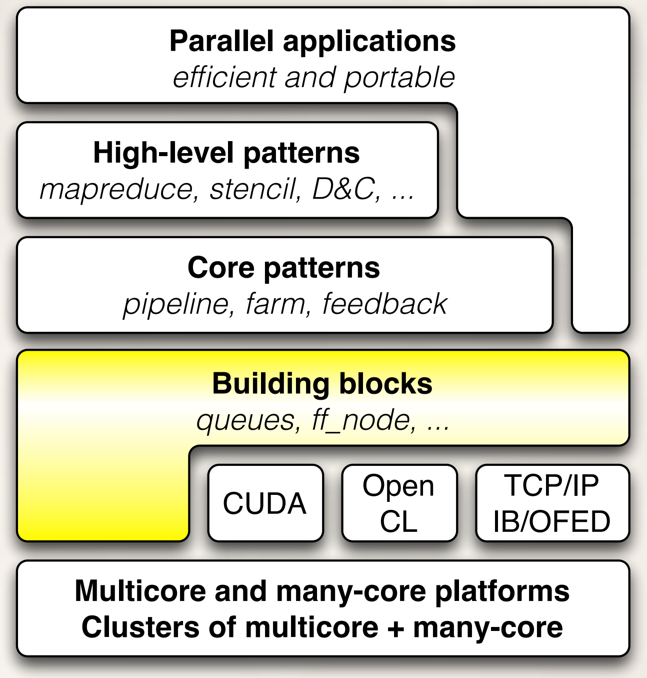
Sao Paulo, Brasil

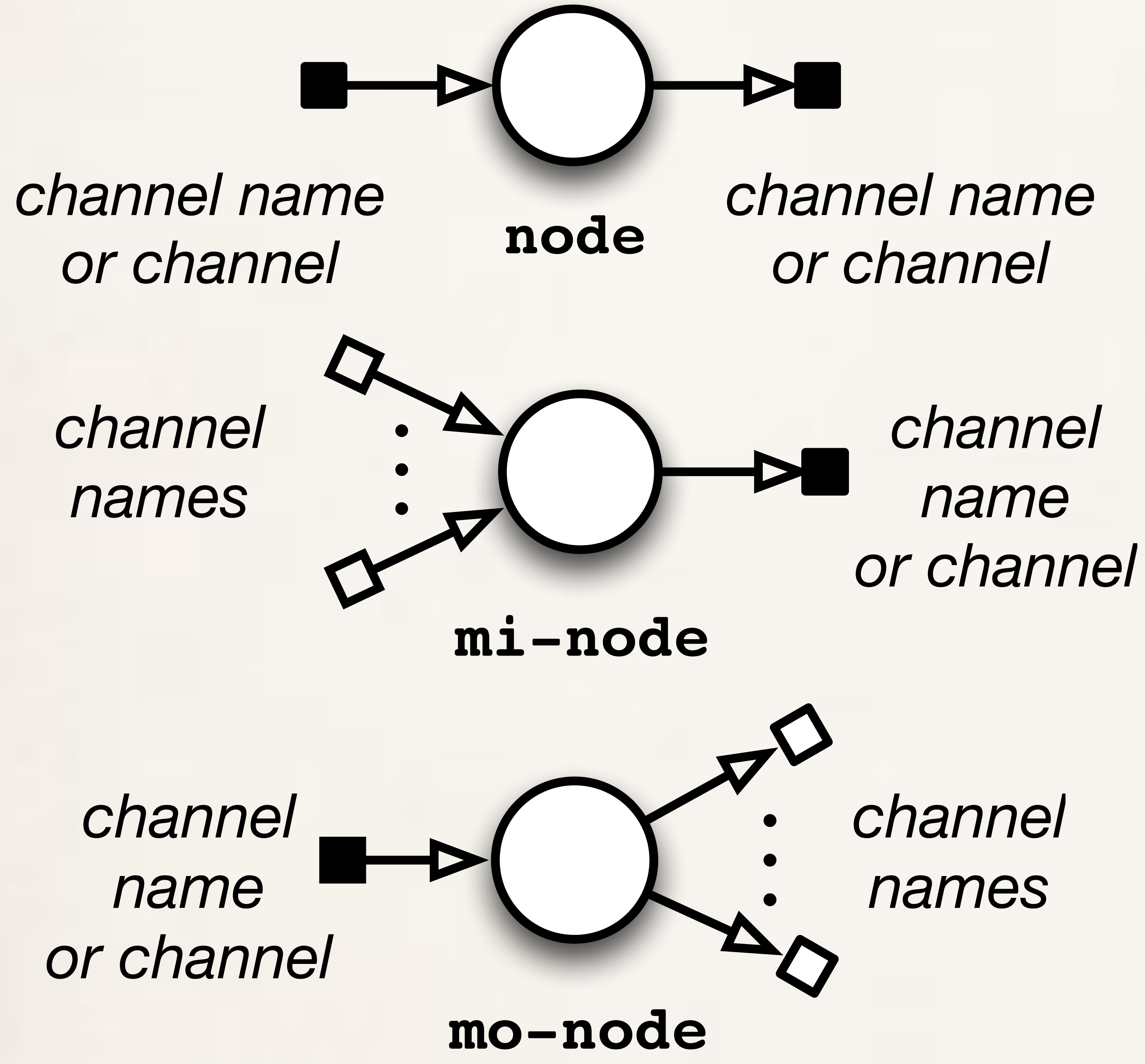
FastFlow (FF)

- C++ header-only library
  - Portable everywhere exists a C++ compiler
  - Originally designed for high-frequency streaming
- Provides stream-oriented and data-parallel patterns
  - compositional, efficient
- Accommodate diversity
  - if you need a different pattern, do it extending a C++ class
- Multi-core, GPGPUs, distributed
- https://sourceforge.net/projects/mc-fastflow



FF building blocks: nodes and channels





threads or processes
threads are non-blocking
(can be suspended using
a native protocol)

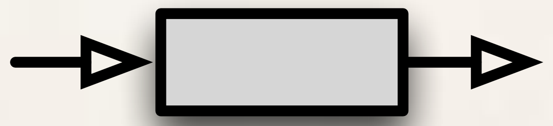
FF bound shmem FIFO channel

Single-Producer-Single-Consumer lock-free fence-free queue

FF unbound shmem FIFO channel

Single-Producer-Single-Consumer lock-free fence-free queue

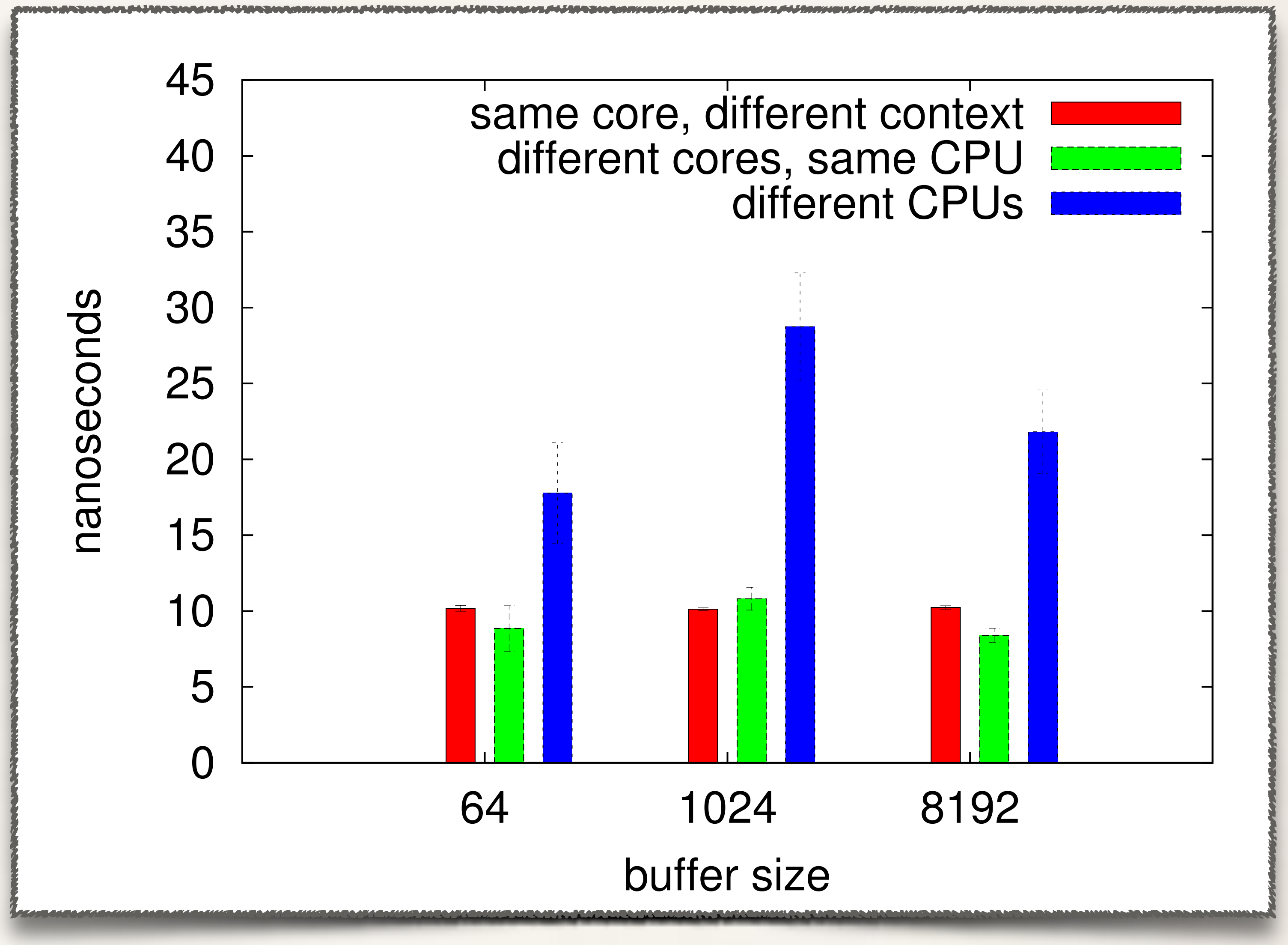
shmem channels communicate pointers in a message passing style



Distributed zero-copy channel

0MQ/TCP or native IB/OFED

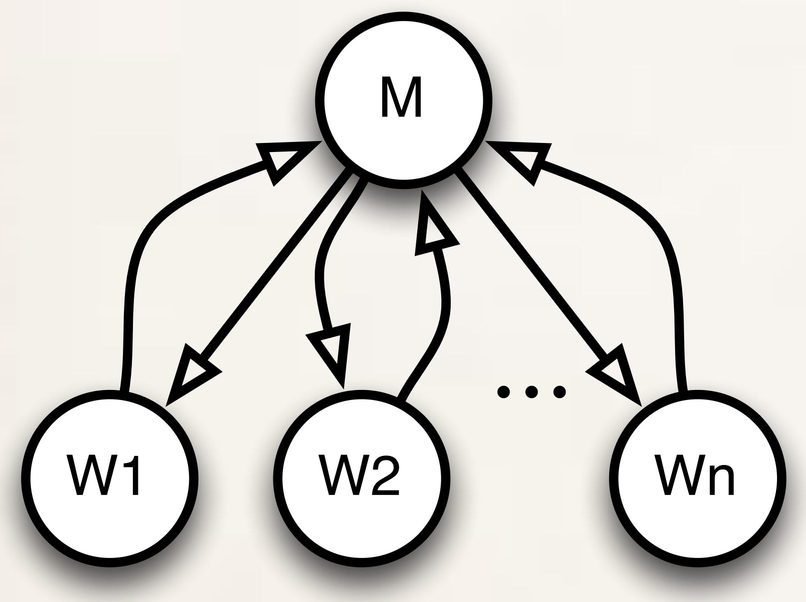
Xeon E7-4820 @2.0GHz Sandy Bridge

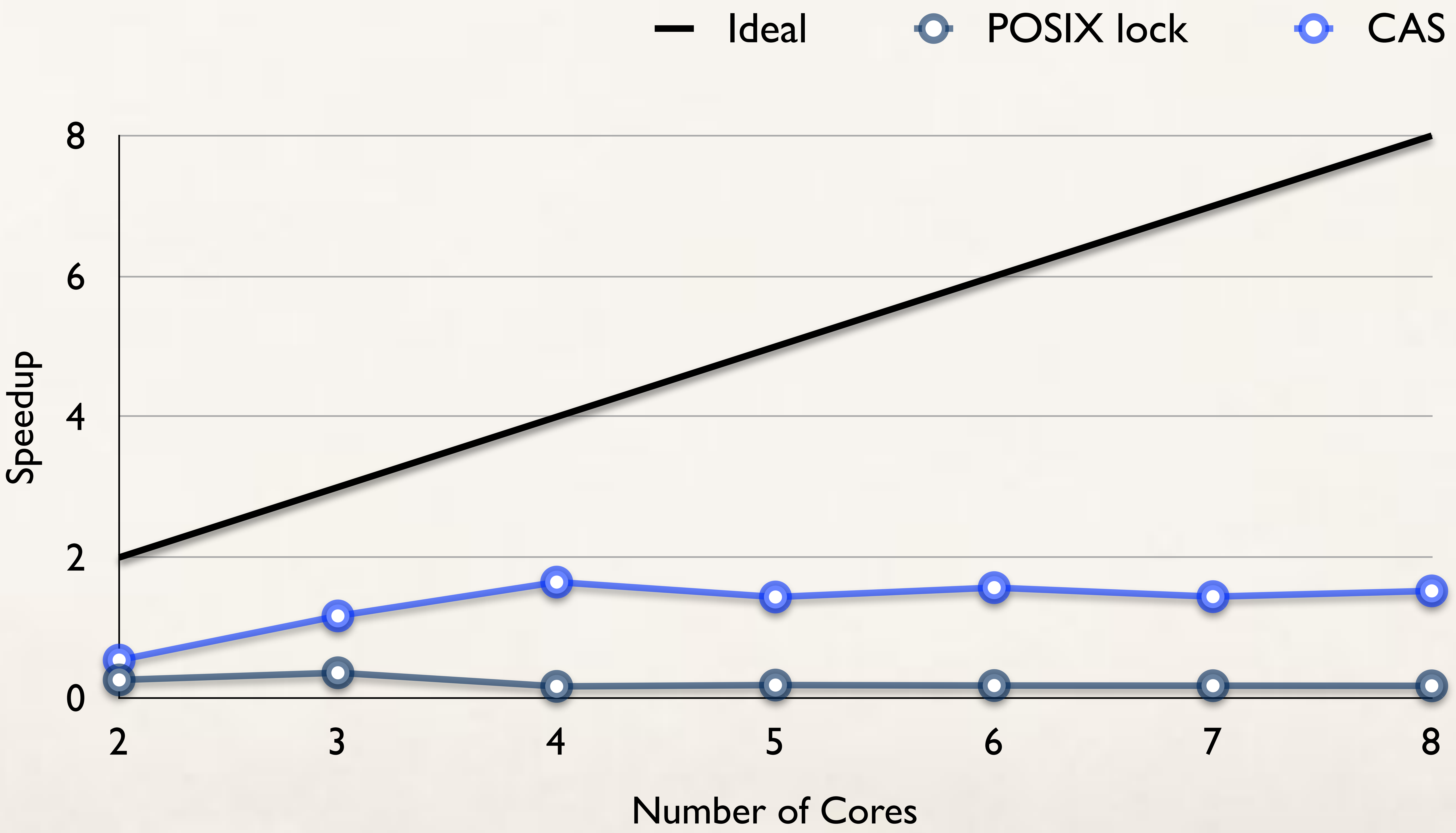


- MVAPICH ~ 190ns
- faster and more scalable than CAS/test-and-set implement.

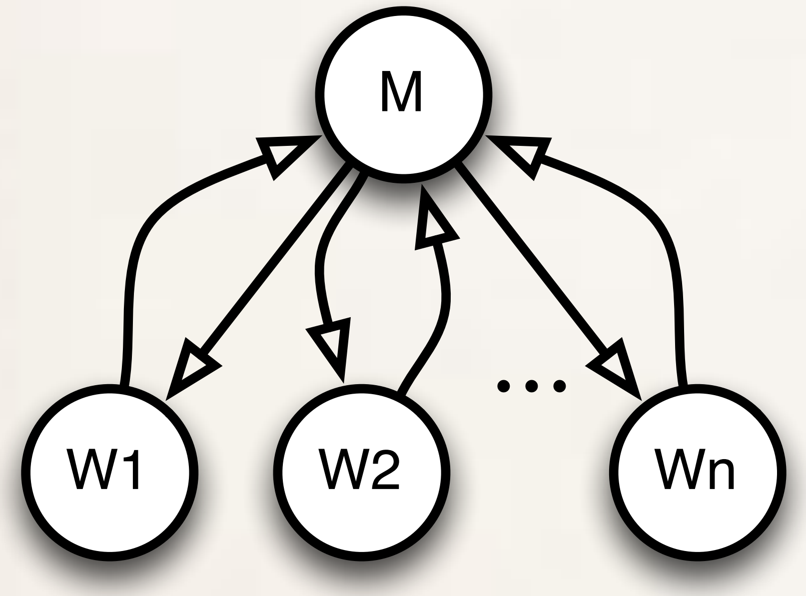
M. Aldinucci and M. Danelutto and P. Kilpatrick and M Meneghin. An Efficient Synchronisation Mechanism for Multi-Core Systems. Euro-Par 2012. LNCS.

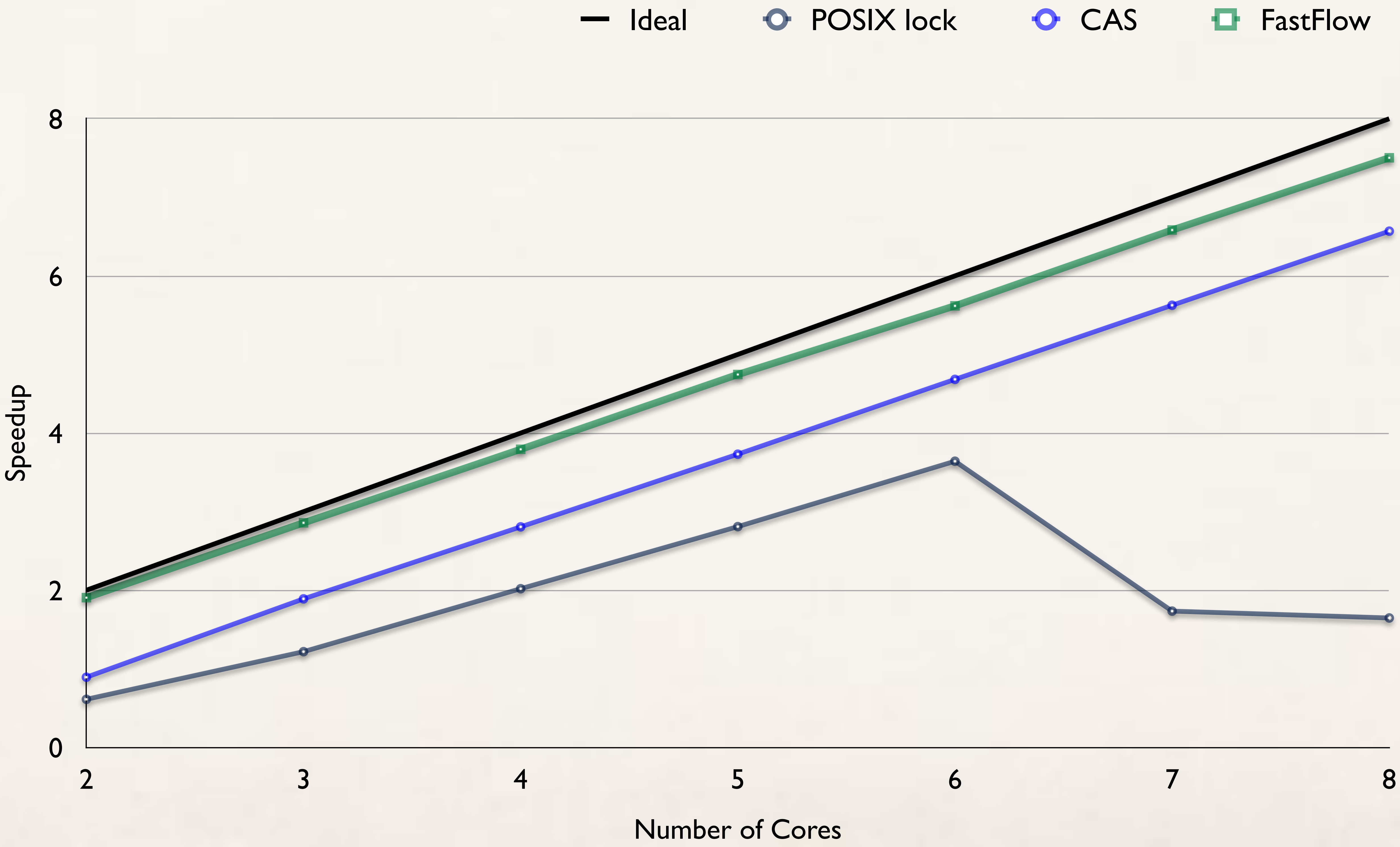
Master-workers (0.5 µS workload)



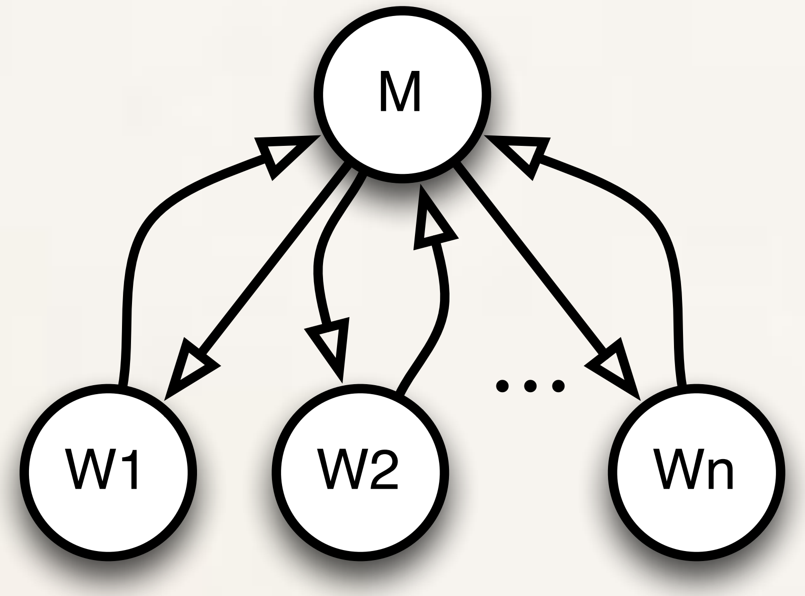


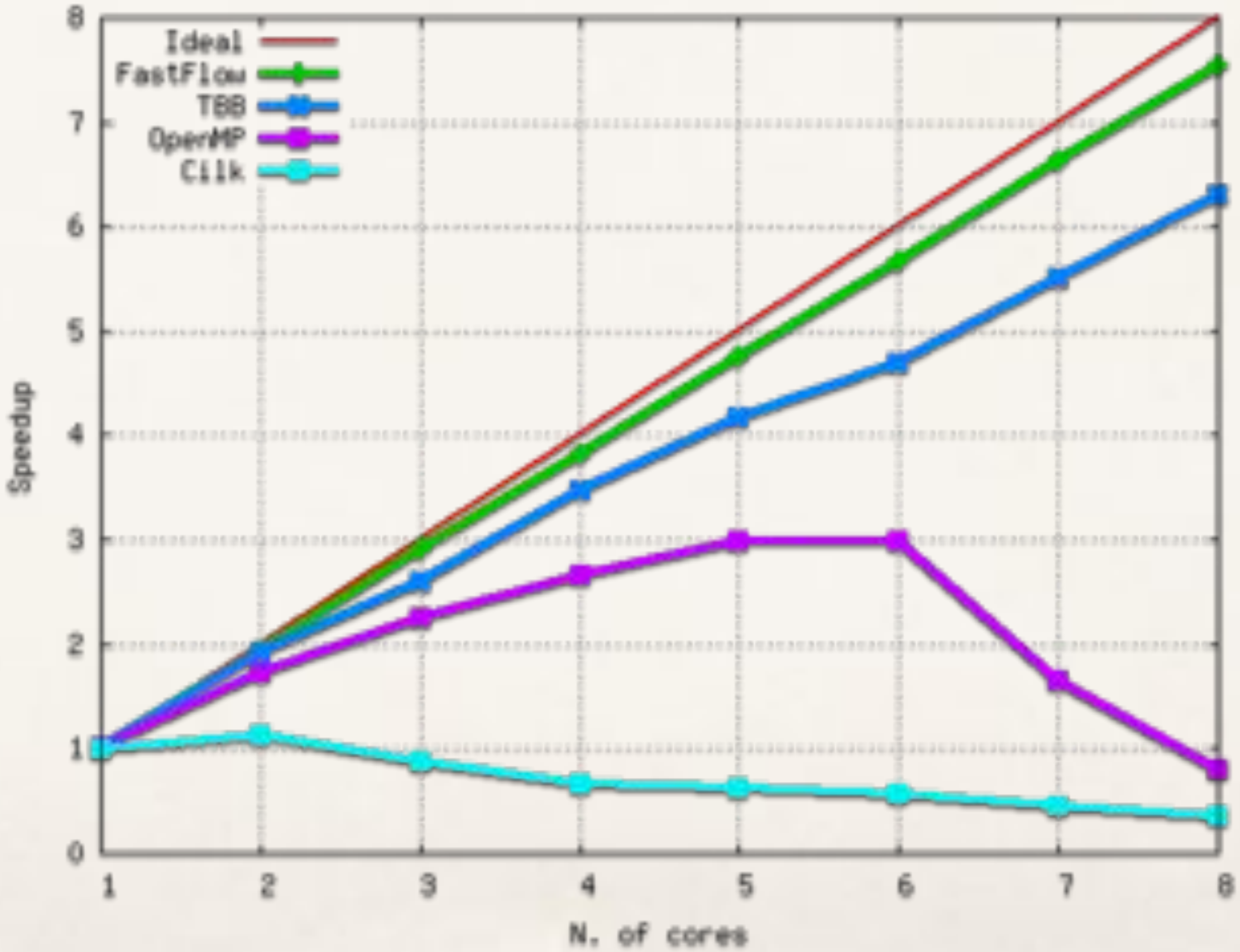
Master-workers (5 μS workload)



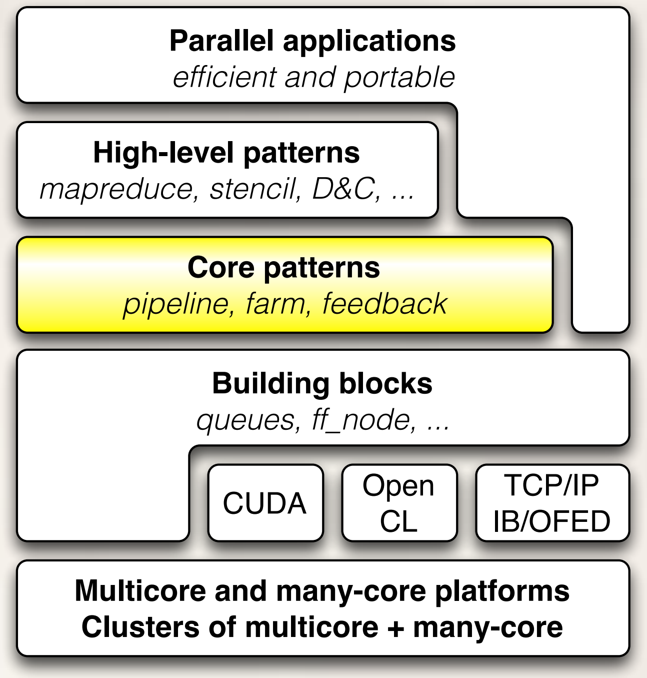


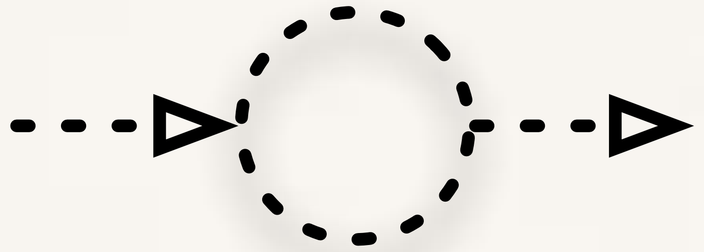
Master-workers (5 μS workload)





Semantics of the node: dataflow activation





ff_node

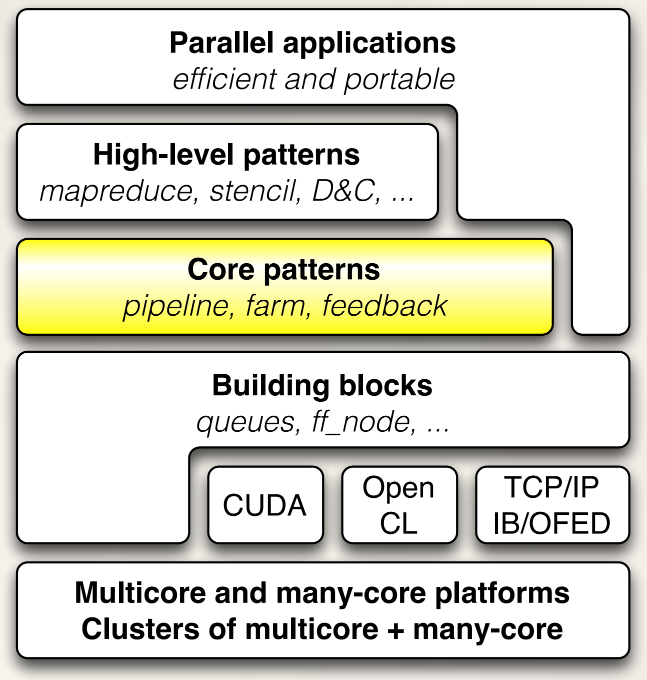
mynode is created as a standard C++ class extending ff_node

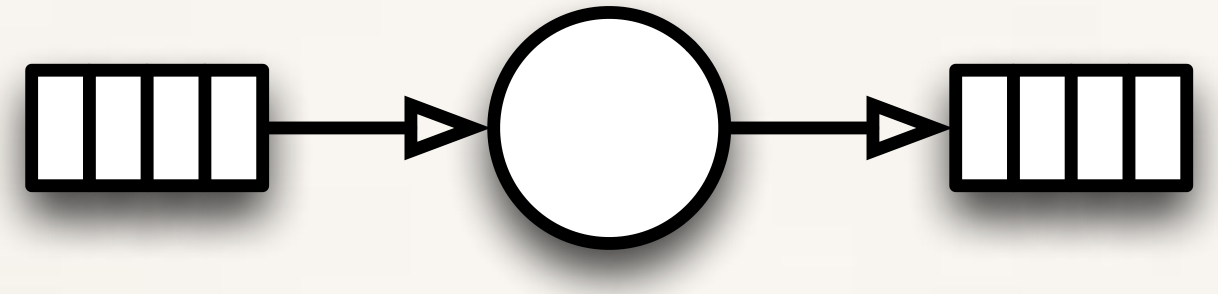
```
class mynode: public ff_node {
public:
    int   svc_init() {
        /* after constructor - running as a thread */
        return 0;
    }

    void * svc(void * task) {
        int * t = (mytask_t *) task;
        // do something on task
        cout << “mynode "<< ff_node::get_my_id()
             << " received task " << t->payload << "\n";
        return task;
     }

    void  svc_end() {
        /* before destructor - running as a thread */
    }
};
```

Semantics of the node: dataflow activation





ff_node

After class construction
mynode is turn into a thread

Nodes are not tasks (as in TBB), they are executors

The svc_init() method is executed

```
class mynode: public ff_node {
public:
    int   svc_init() {
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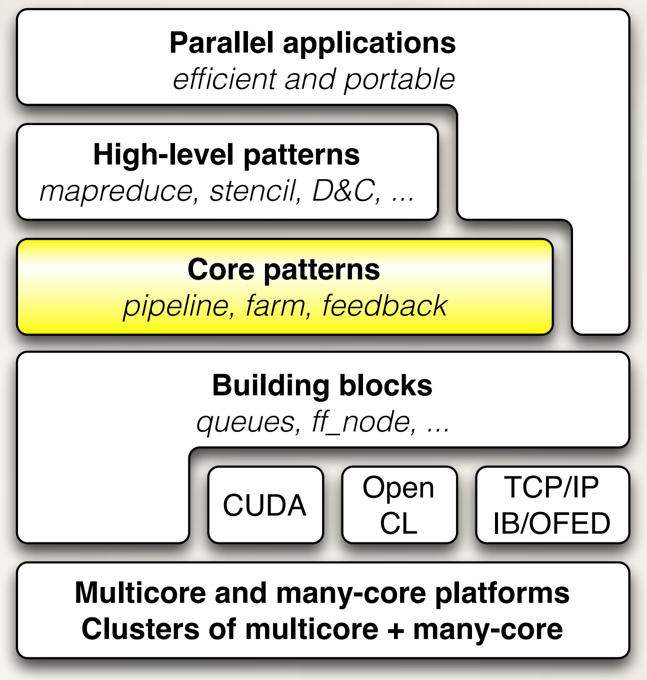
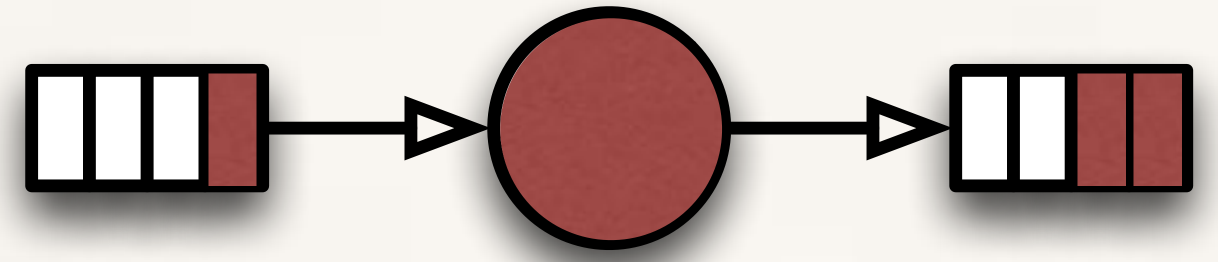




ff_node

the node enters in a infinite loop

1. get a task from input channel (i.e. a pointer)
2. execute svc method
3. put a task the output channel (i.e. a pointer)

svc() might output more tasks via ff_send_out call (not shown)

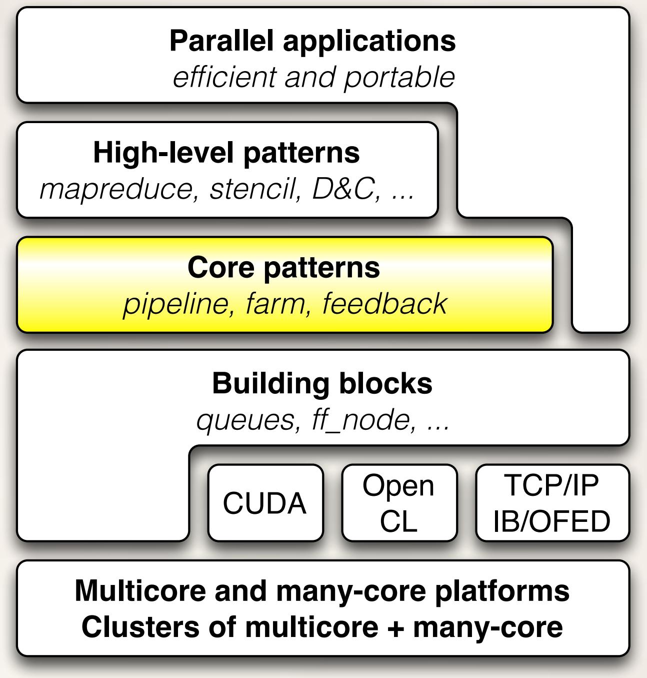
The node terminate on returning a NULL pointer

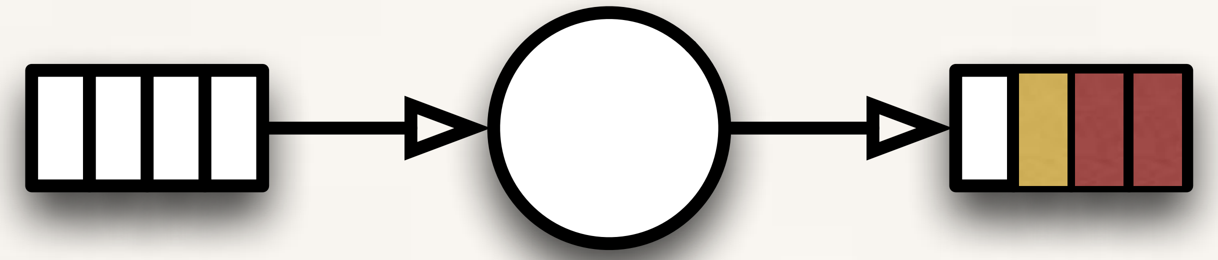
```
class mynode: public ff_node {
public:
    int   svc_init() {
       /* after constructor - running as a thread */
       return 0;
    }

    void * svc(void * task) {
       int * t = (mytask_t *) task;
       // do something on task
       cout << “mynode "<< ff_node::get_my_id()
            << " received task " << t->payload << "\n";
       return task;
     }

    void  svc_end() {
       /* before destructor - running as a thread */
    }
};
```

Semantics of the node: dataflow activation





ff_node

svc_end is executed before class destruction

termination token is propagated to the next node

```
class mynode: public ff_node {
public:
    int   svc_init() {
        /* after constructor - running as a thread */
        return 0;
    }

    void * svc(void * task) {
        int * t = (mytask_t *) task;
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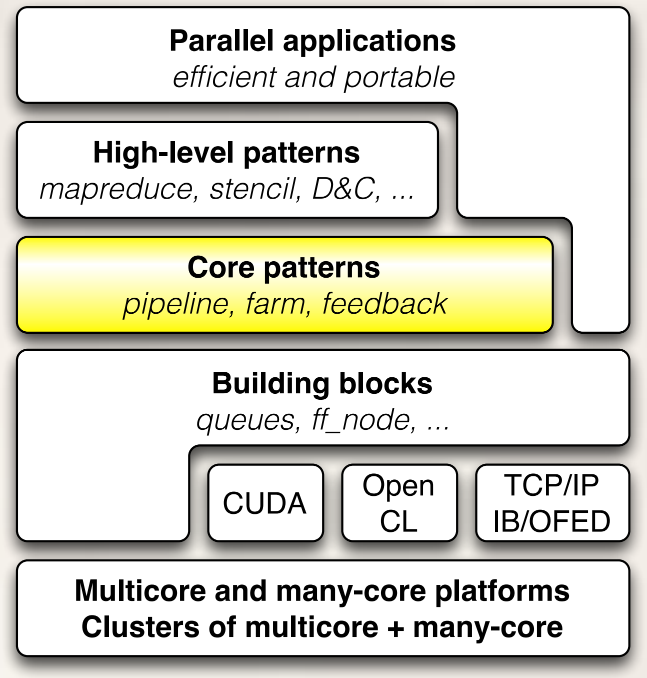
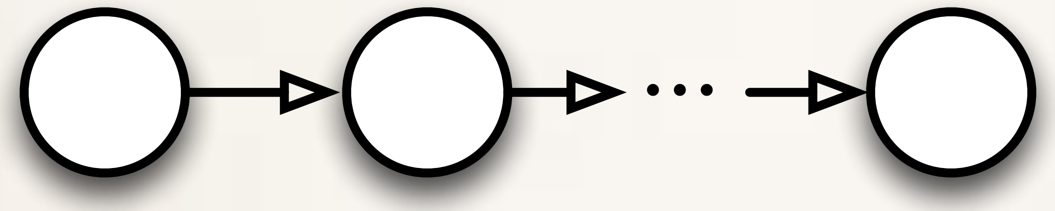
        cout << “mynode "<< ff_node::get_my_id()
             << " received task " << t->payload << "\n";
        return task;
     }

    void  svc_end() {
        /* before destructor - running as a thread */
    }
};
```

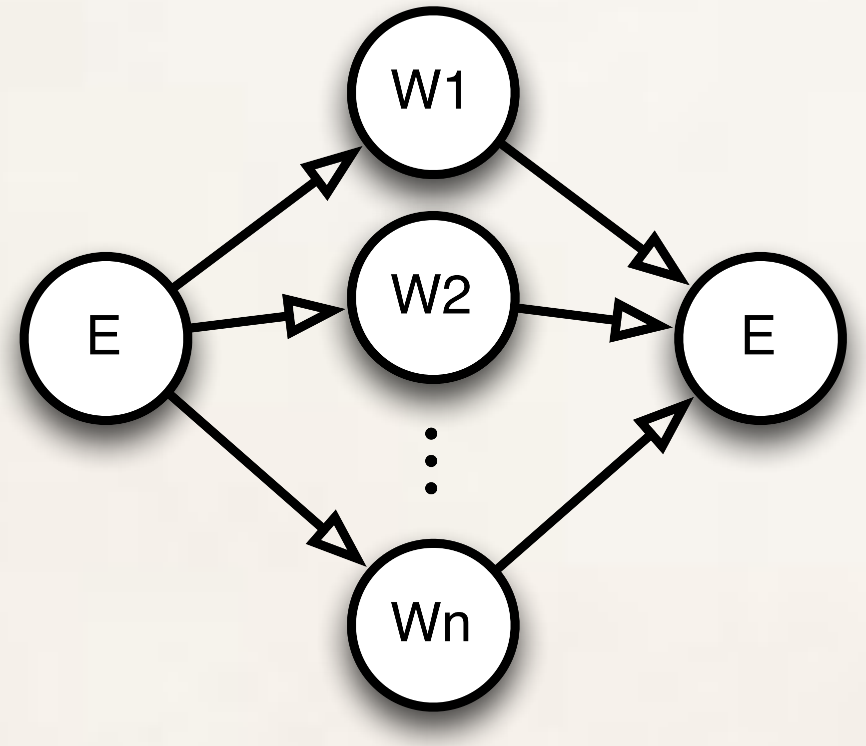
FF core patterns: pipe, farm, feedback
they are streaming networks, not task graphs



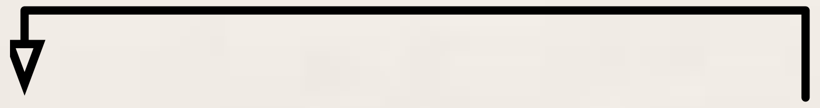
pipeline



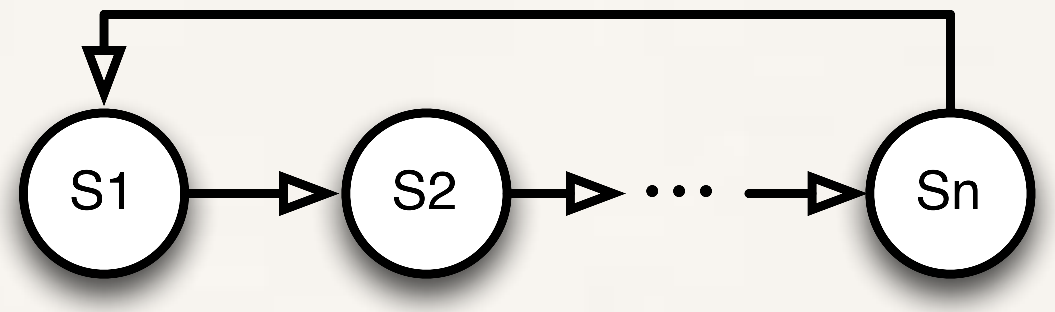
farm



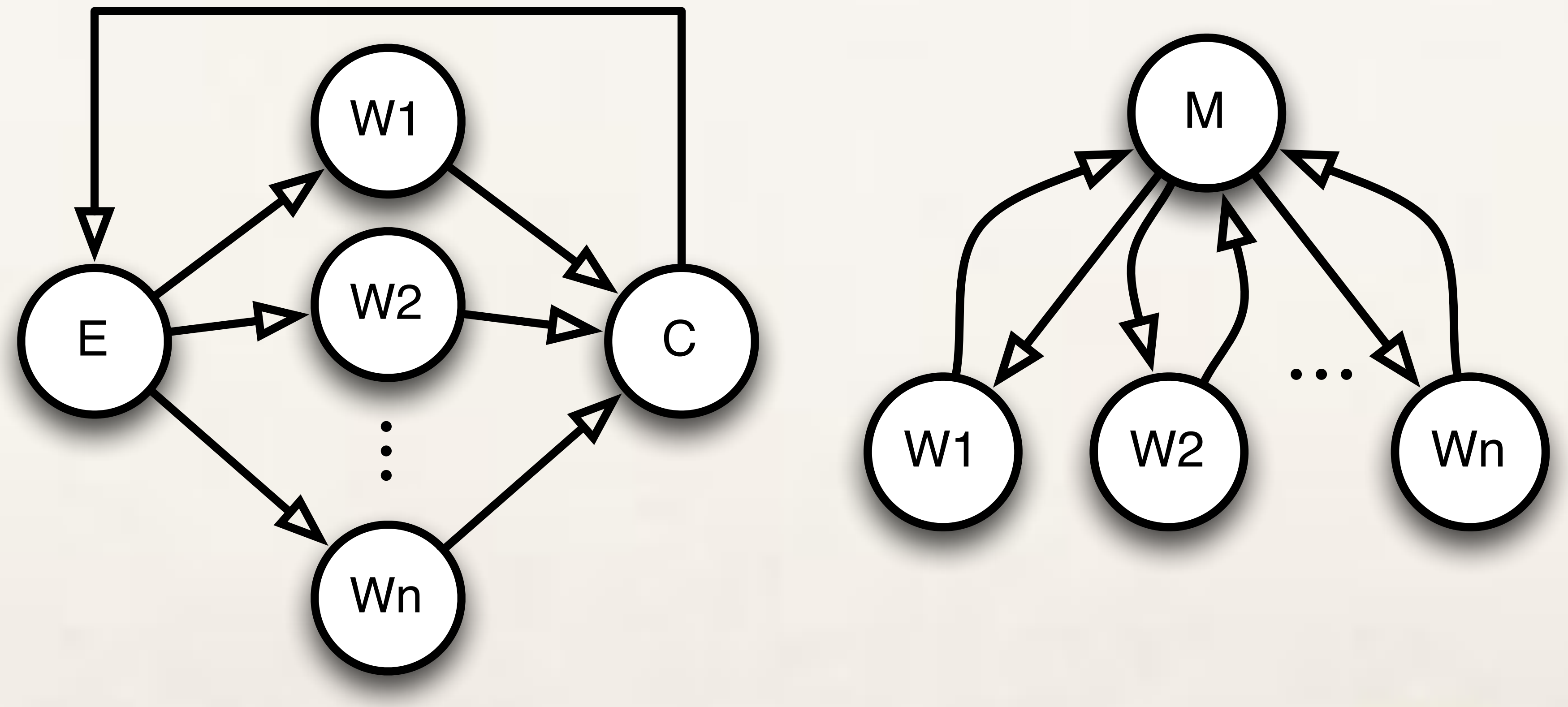
feedback



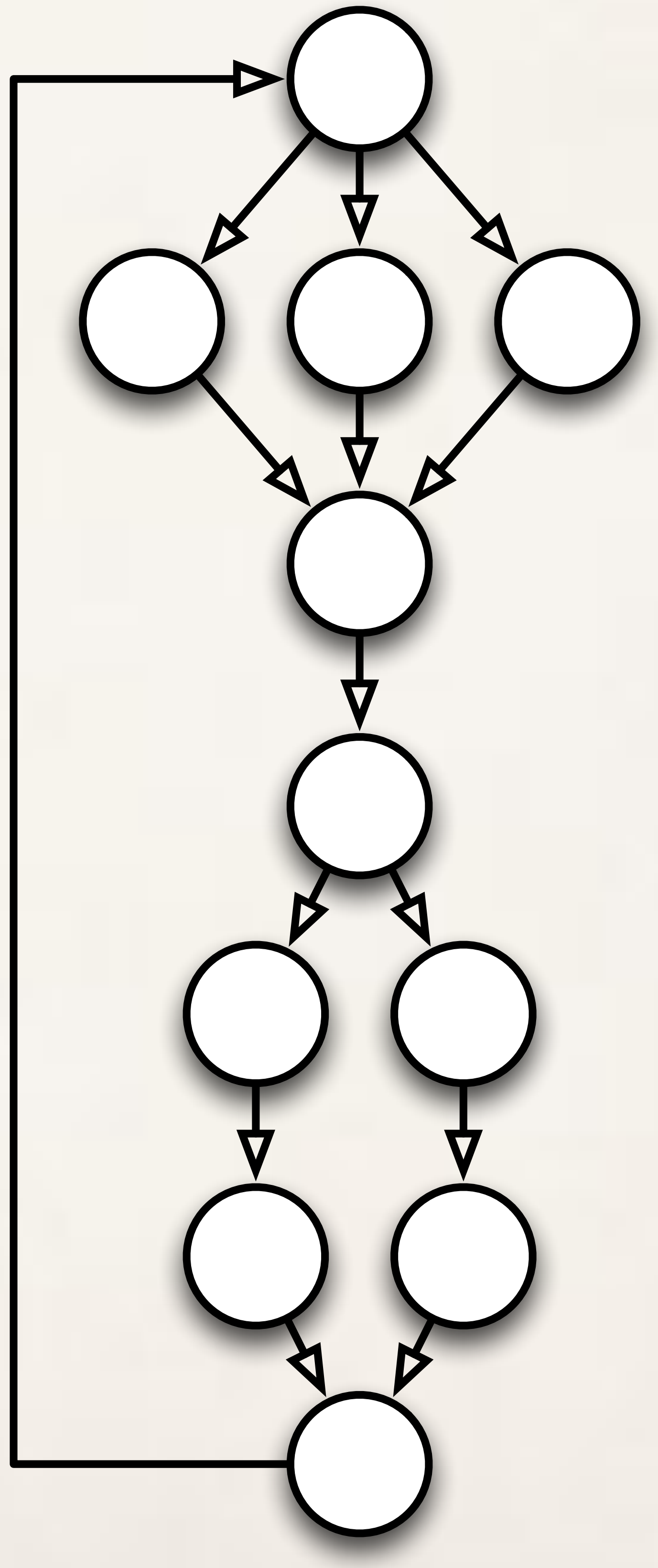
pipeline with feedback



farms with feedback
(e.g. D&C and Master-Workers)



or any composition of them



```cpp
#include <vector>
#include <iostream>
#include <ff/farm.hpp>


using namespace ff;

// generic worker
class Worker: public ff_node {
public:
    void * svc(void * task) {
        int * t = (int *)task;
        std::cout << "Worker " << ff_node::get_my_id()
                  << " received task " << *t << "\n";
        return task;
    }
    // I don't need the following functions for this test
    //int   svc_init() { return 0; }
    //void  svc_end() {}

};

// the gatherer filter
class Collector: public ff_node {
public:
    void * svc(void * task) {
        int * t = (int *)task;
        if (*t == -1) return NULL;
        return task;
    }
};

// the load-balancer filter
class Emitter: public ff_node {
public:
    Emitter(int max_task):ntask(max_task) {};

    void * svc(void *) {
        int * task = new int(ntask);
        --ntask;
        if (ntask<0) return NULL;
        return task;
    }
private:
    int ntask;
};
```

```cpp
int main(int argc, char * argv[]) {

    if (argc<3) {
        std::cerr << "use: "
                  << argv[0]
                  << " nworkers streamlen\n";
        return -1;
    }

    int nworkers=atoi(argv[1]);
    int streamlen=atoi(argv[2]);

    if (!nworkers || !streamlen) {
        std::cerr << "Wrong parameters values\n";
        return -1;
    }

    ff_farm<> farm; // farm object

    Emitter E(streamlen);
    farm.add_emitter(&E);

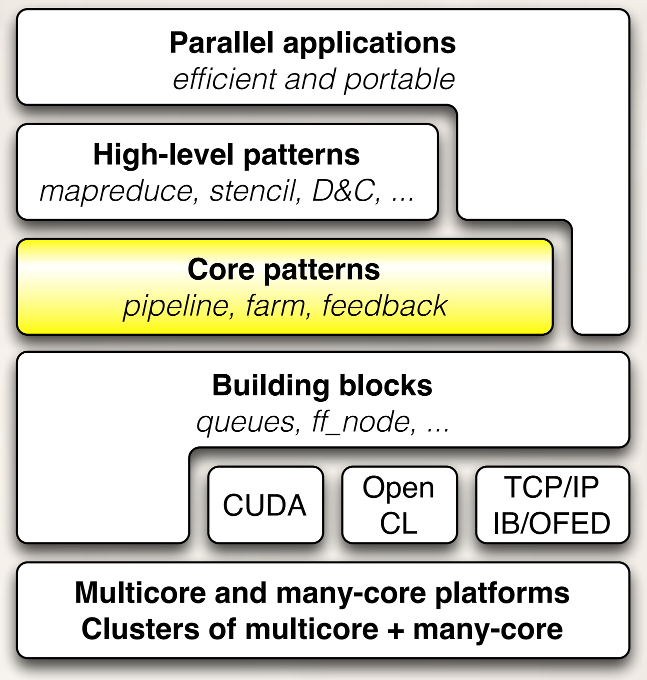
    std::vector<ff_node *> w;
    for(int i=0;i<nworkers;++i) w.push_back(new Worker);
    farm.add_workers(w); // add all workers to the farm

    Collector C;
    farm.add_collector(&C);

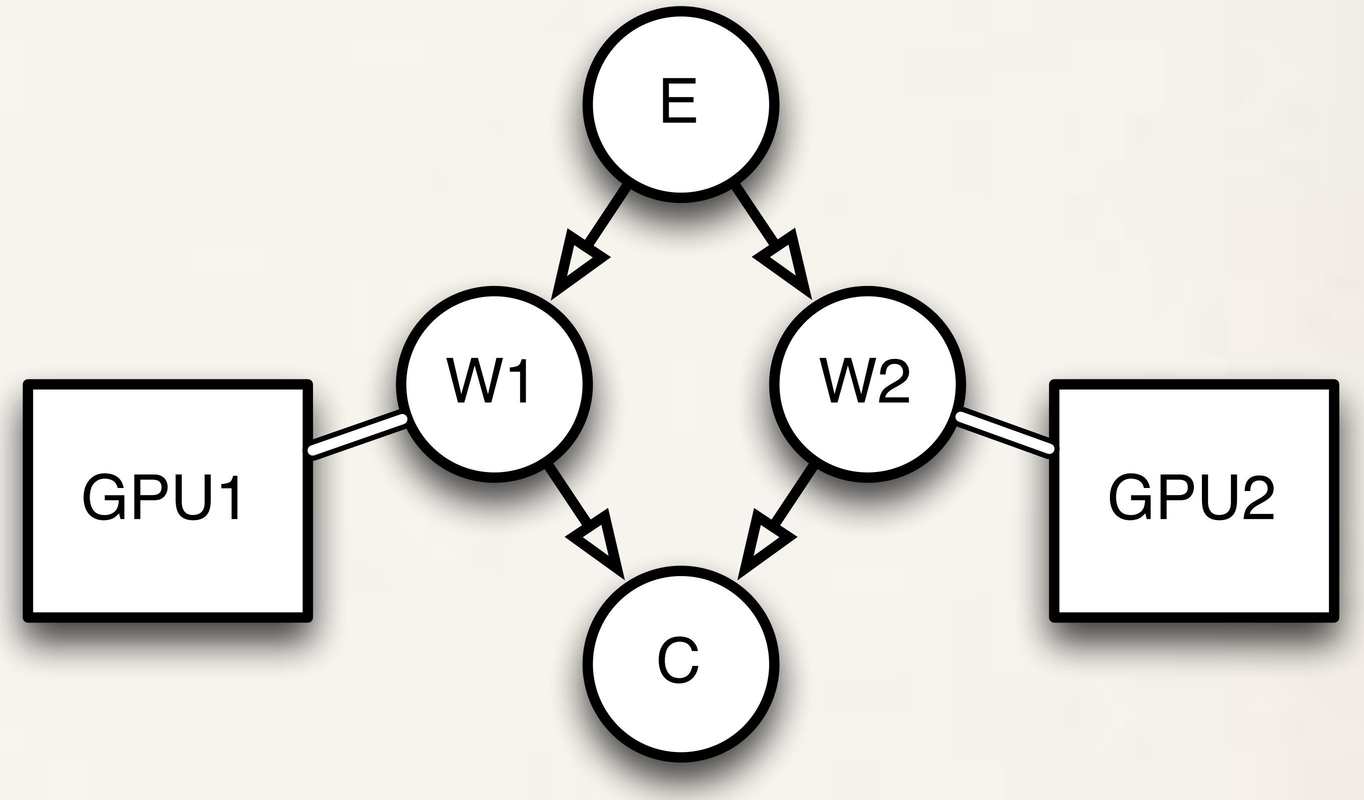
    if (farm.run_and_wait_end()<0) {
        error("running farm\n");
        return -1;
    }
    std::cerr << "DONE, time= " << farm.ffTime() << " (ms)\n";
    farm.ffStats(std::cerr);

    return 0;
}
```

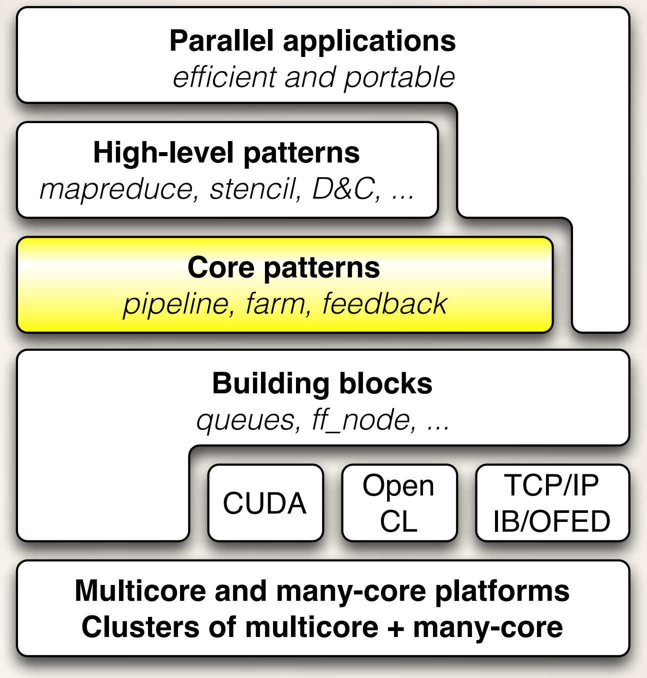
GPGPUs



- Fill stencilReduce methods with CUDA kernel code
  - No CUDA-related host code at all need to be written
- Possibly nest stencilReduce into another pattern
  - e.g. farm to use many GPGPUs
    - the async copy engine is automatically used via CUDA streams
  - Helpful to mix threading (or distributed) with GPGPUs
  - If you already have your standard host+CUDA code just copy-paste into a svc( ) method

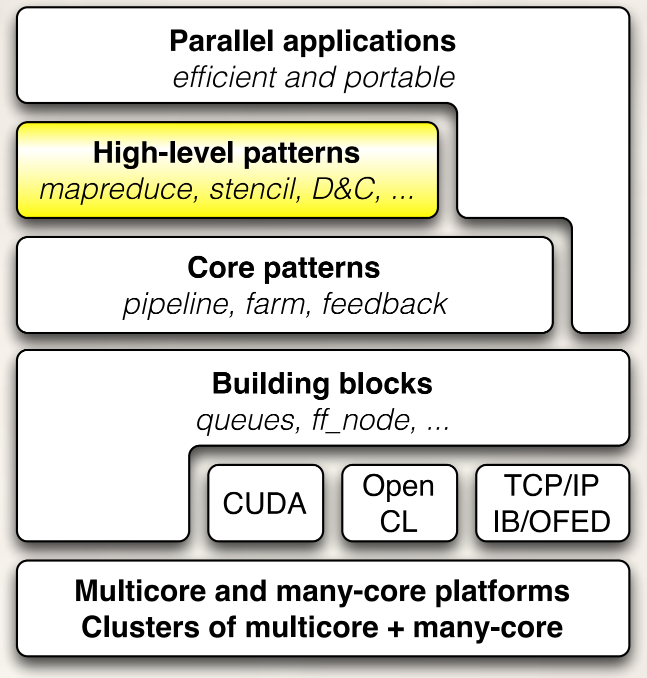


FF core patterns: rationale



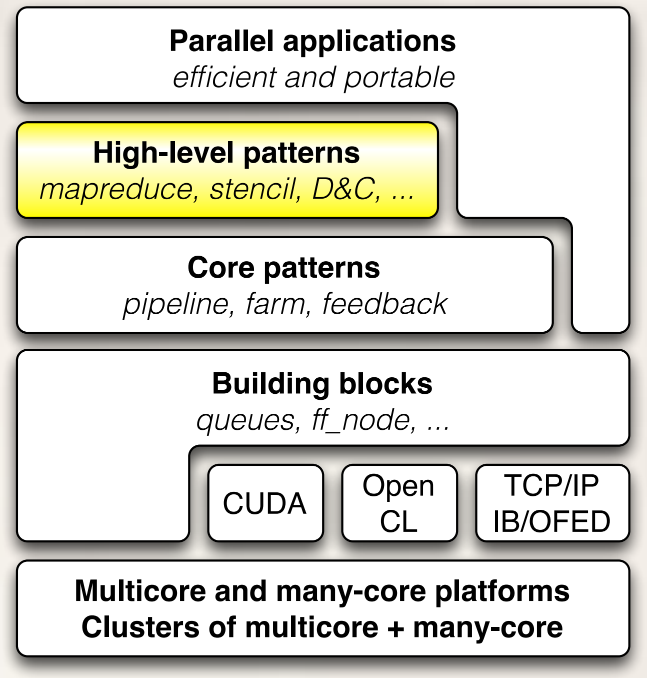
- farm: process in parallel independent tasks (e.g. C++ objects)
  - true dependencies are enforced only along edges of the graph
  - workers might synchronise (e.g. w locks/atomics), synchronisation in the business code
- farm, pipeline and feedback (to build cyclic networks) are enough to write all other patterns
- Think to GPGPUs design
  - They be though as machines to compute a map, reduce, stencil, …
  - … but in hardware they are built as a farm that dispatches independent blocks onto multiprocessors (+global memory)

FF high-level patterns



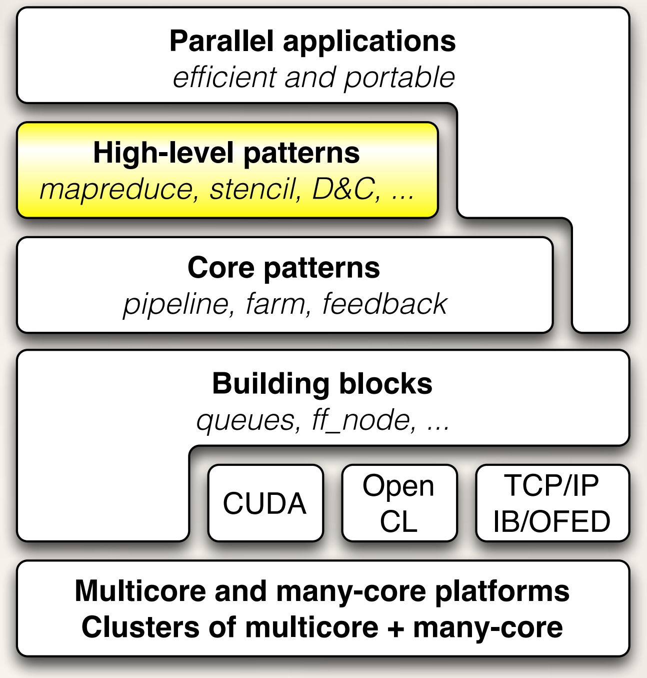
- Proposed as code annotations
  - Similarly to openMP, openacc, …
  - used to generate a graph at the core pattern level
- Examples
  - parallel_for
  - map, reduce, MapReduce, … (targeting GPGPUs)
  - and as many as you want: developing a new pattern is just developing a new class

Example: map (derived from stencilReduce)



- 2 or more GPGPUs on the same platform
  - nest a stencilReduce, map, reduce … into a (host) farm with 2 workers
  - (future: we need to understand how to use NVLINK)
- offload code onto distributed GPGPUs
  - nest a stencilReduce, map, reduce … into a (host) distributed farm with 2 workers
  - data serialisation is up to user, the framework just provides callback to do it
- In both cases
  - be sure that tasks are independent (otherwise you need another pattern)

Example: map (derived from stencilReduce)




```
FFMAPFUNC(mapF, unsigned int, in, return (in * 2););

class cudaTask: public baseCUDATask<unsigned int> {
public:
    void setTask(void* t) {
        if (t) {
            cudaTask *t_ = (cudaTask *) t;
            setInPtr(t_->in);     // match of data pointer H2D
            setOutPtr(t_->in);    // match of data pointer D2H
            setSizeIn(inputsize); // needed without Unified memory
        }
    }
    unsigned int *in, *out;
};

main () {
…
// put the input in task->in
FFMAPCUDA(cudaTask, mapF) *myMap = new FFMAPCUDA(cudaTask, mapF)(*task);
myMap->run_and_wait_end();
// result is in task->out
…
}
```

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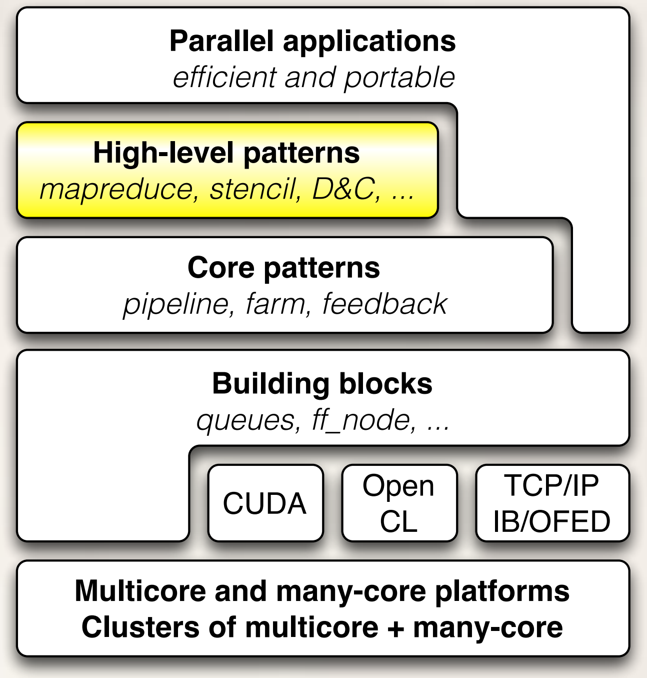


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…
}
```

This is CUDA code

Simple in this case, but any CUDA code is valid here
It will be compiled with NVCC

This is just a name to distinguish this kernel

This is a macro

For multicore we use C++11 lambda. Theoretically possible to use Lambda for kernel code? (maybe with UnifiedMemory)

GPGPU code: Rationale

- Is it worth abstract even more?
  - In particular, the the CUDA code
- No, we believe
  - Often not needed: CUDA code if often C++ code
  - Access to thread_id, always needed
  - Programmers would like to super-optimize their code
    - using all CUDA features
  - CUDA evolves too rapidly

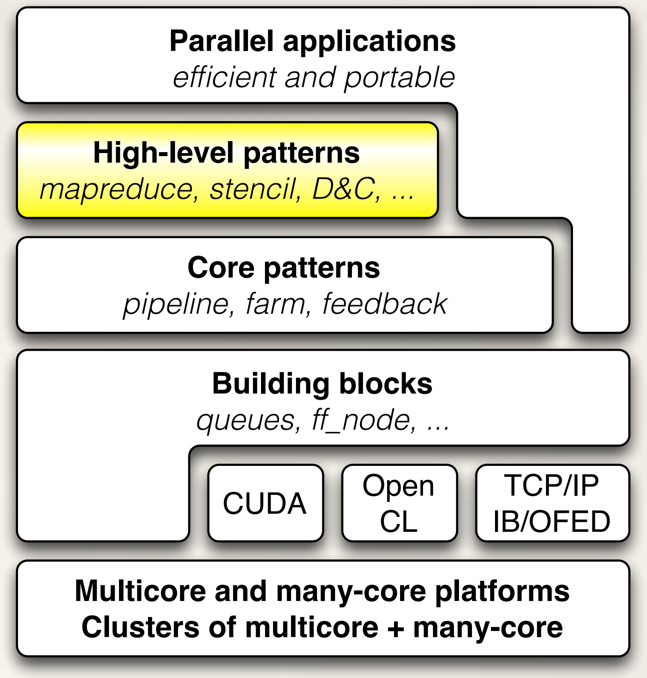
“Demo”

map, farm(map), …

“Demo”

denoiser

Example: Qt-mandelbrot (from Qt samples)



Original (sequential)

```
…
const int Limit = 4;
bool allBlack = true;
if (restart) break;
if (abort) return;

for (int y = -halfHeight; y < halfHeight; ++y) {

uint *scanLine =
     reinterpret_cast<uint *>(image.scanLine(y + halfHeight));
double ay = centerY + (y * scaleFactor);
…
}
private:

…
```

FastFlow (parallel)

```
…
const int Limit = 4;
bool allBlack = true;
if (restart) break;
if (abort)   return;

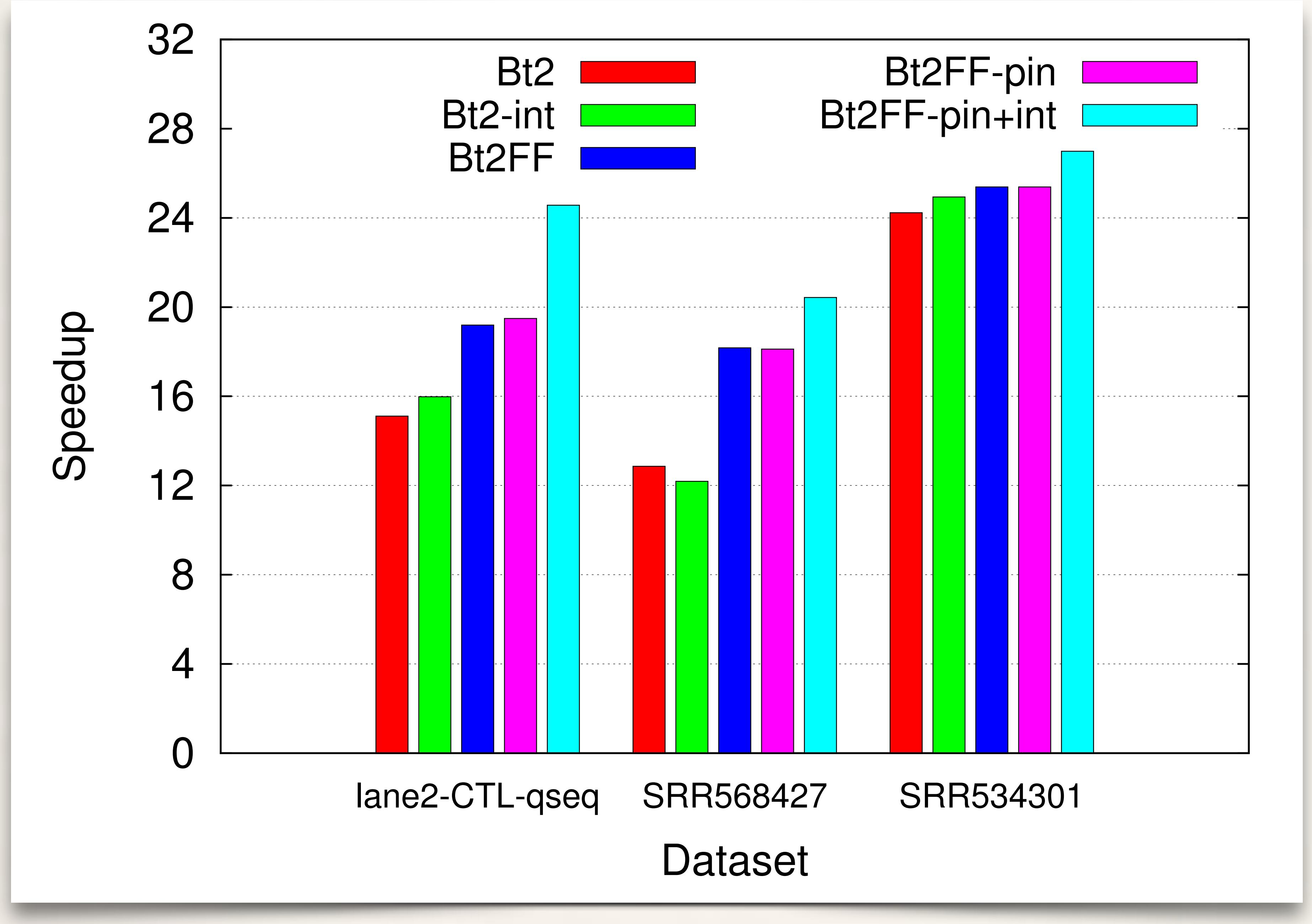
pf_det.parallel_for(-halfHeight, halfHeight, 1, halfHeight,
                    [&](const long y) {
uint *scanLine =
     reinterpret_cast<uint *>(image.scanLine(y + halfHeight));
double ay = centerY + (y * scaleFactor);
…
}
private:
ParallelFor pf_det;
…
```

“Demo”

mandelbrot

Performance (multicore)

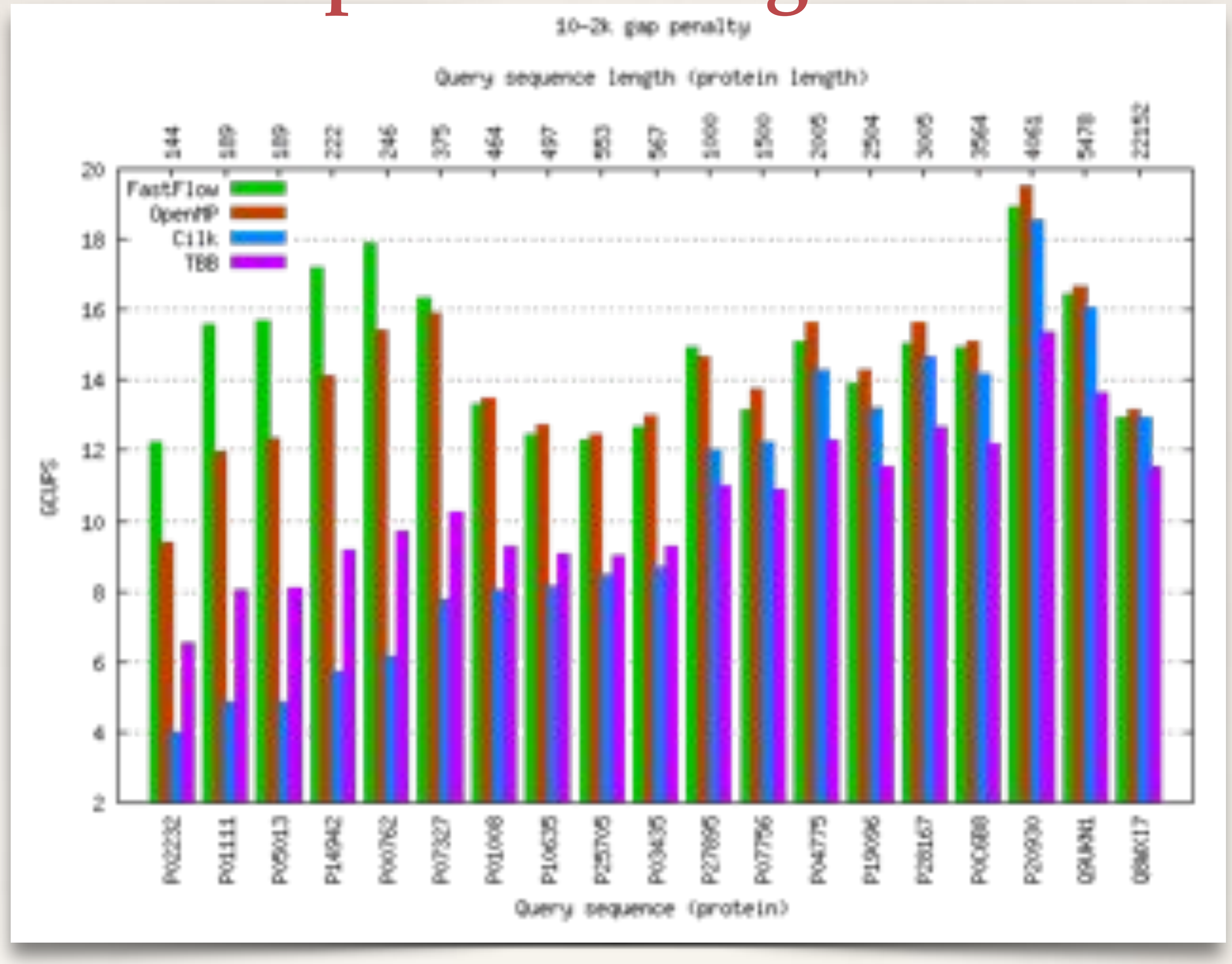
Bowtie2 tool (DNA mapping)



Original version: pthreads + test&set spinlocks
FF differs no more than 30 lines of
code from the original on several thousands
(including memory affinity management)

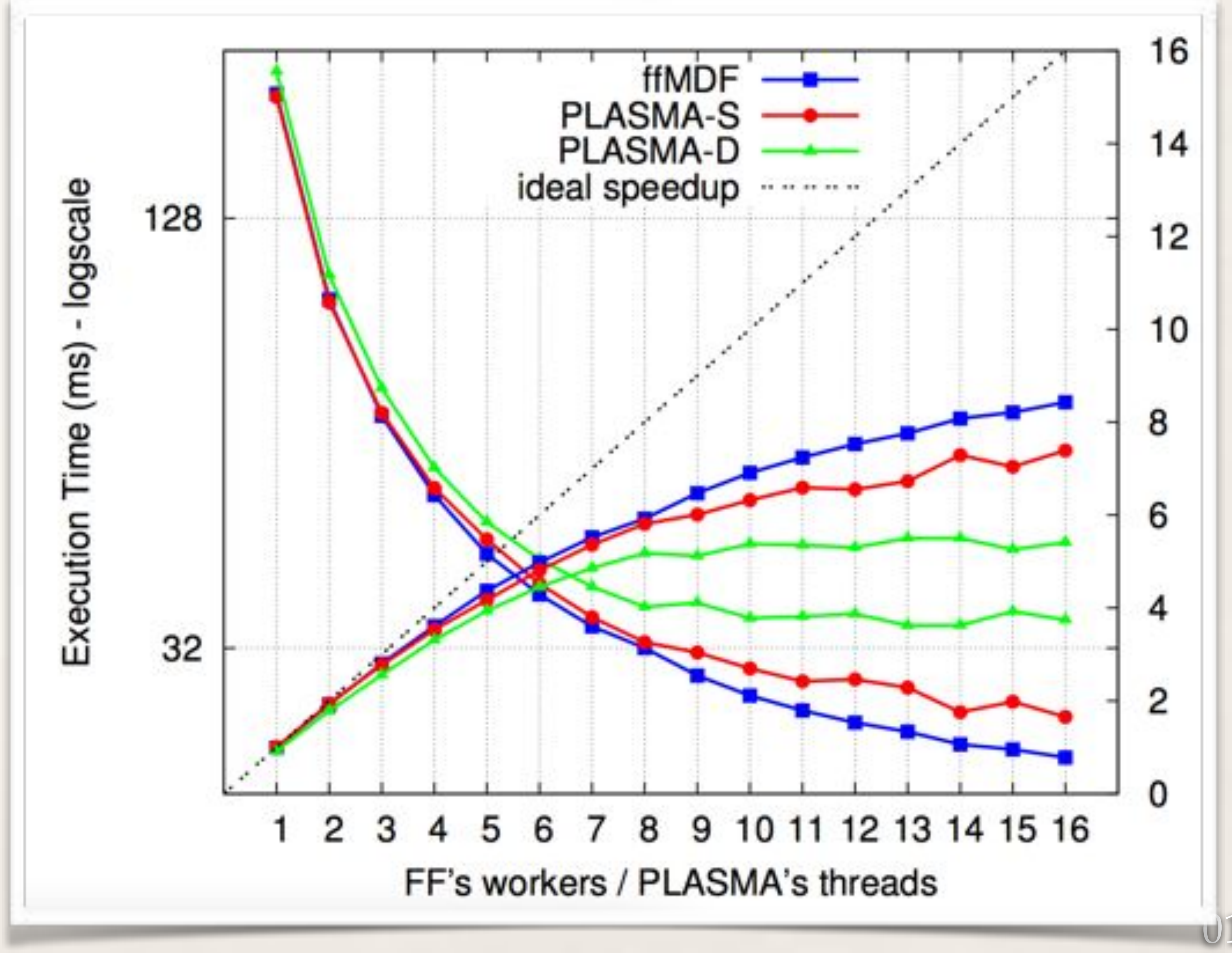
proteine length →

speed →



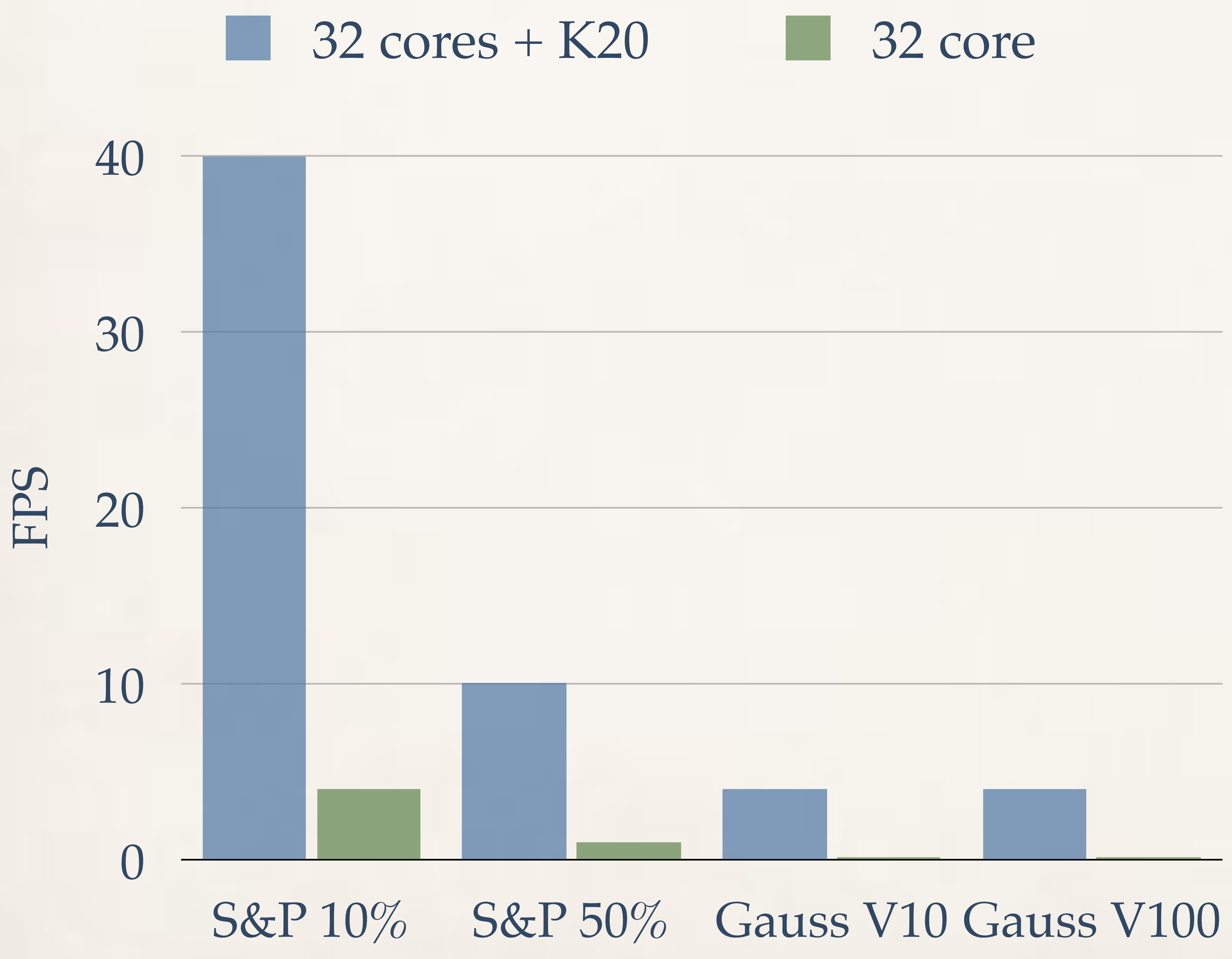
Smith-Waterman (SSE2) against OpenMP, Cilk, TBB

Cholesky LU against PLASMA

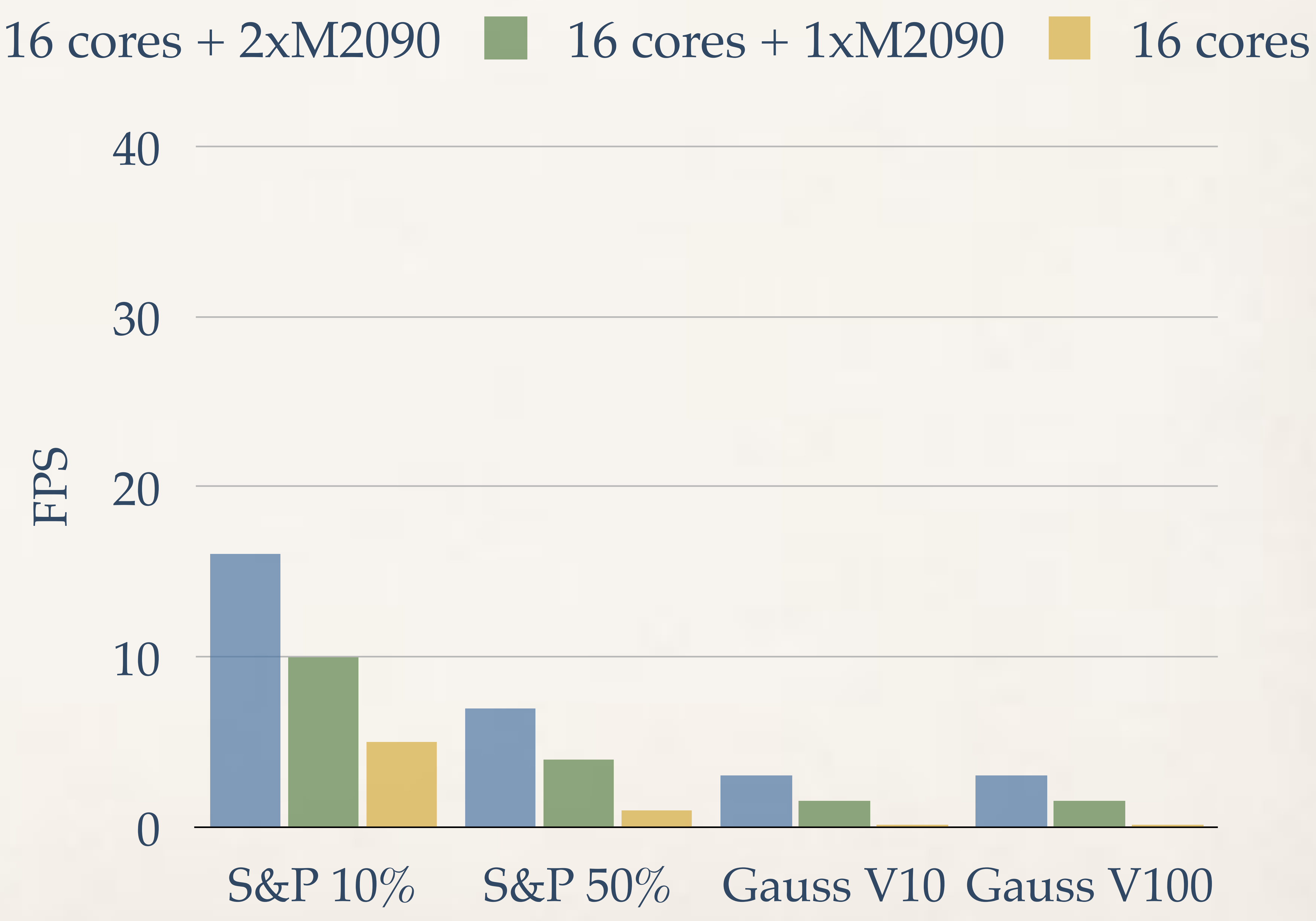


Performance (CPUs + GPGPUs) Video frames 768x512

Nehalem 32 cores + 1 K20



SandyBridge 16 cores + 2 Tesla M2090



no difference w.r.t. hand-written CUDA code

FastFlow: a framework for research

- Open-minded patterns
  - A pattern is missing? Not happy of the implementation? Modify it extending a class …
  - Multicore, GPGPUs, distributed under the same theoretical umbrella. No compilers to modify (!)
  - Non expert programmers does not need to deal with synchronisations and data copies, just select patterns
- Productivity: portability, reduced development time, porting of legacy applications, …
- Comparable or better with OpenMP and TBB on fine grain
  - Comparable with OpenMP on data-parallel - really fast on streaming (especially very high-frequency)
- Entirely C++ (**C++11**), minimalistic design, solid enough to test new solutions
  - E.g. FastFlow lock-free parallel memory allocator extend with CUDA UnifiedMemory
- Main platform is Linux, but works almost everywhere exist a C++ compiler
  - MacOS, Win — x86, x86_64, Xeon Phi, PPC, Arm, Tilera, NVidia (CUDA and OpenCL) — gcc, clang, icc, nvcc

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M. Torquati


M. Danelutto

https://sourceforge.net/projects/mc-fastflow/

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IMPACT
Unito - 440K€

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