

# Synthesizing Code for GPGPUs from Abstract Formal Models

**Gabriel Hjort Blindell**

Christian Menne

Ingo Sander



KTH Royal Institute of Technology, Sweden

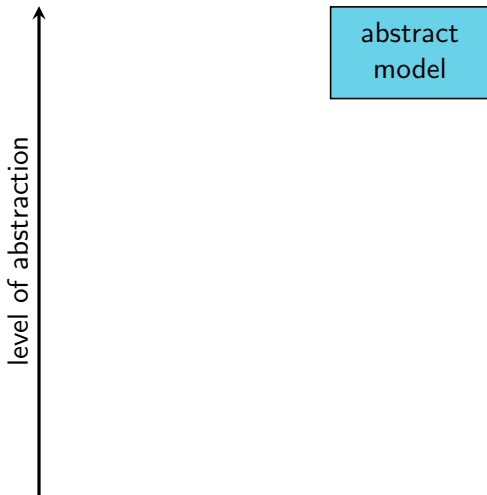
November 20, 2014

SCS Seminar

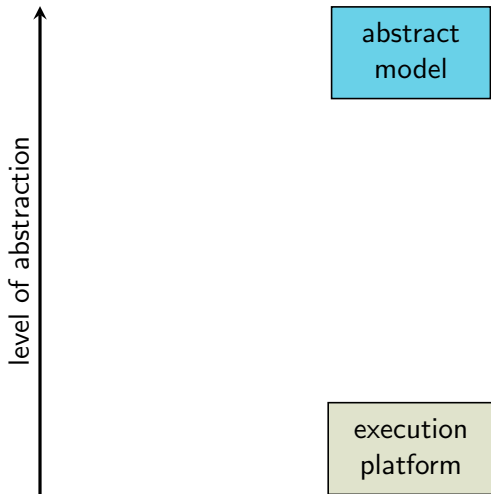
# Paper

Hjort Blindell, G., Menne, C., Sander, I. “Synthesizing Code for GPGPUs from Abstract Formal Models.” Forum on specification & Design Languages (FDL 2014). Munich, Germany, October 14–16, 2014.

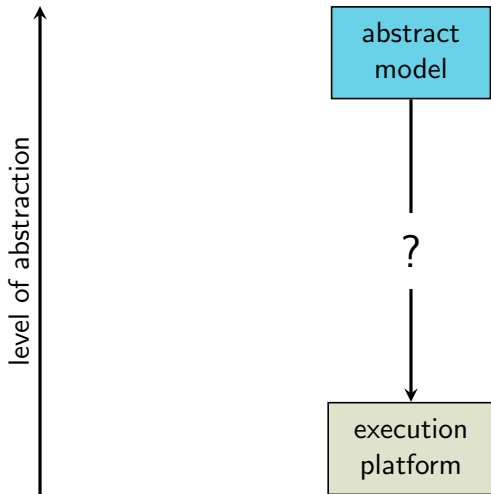
# Ideal: Want to Model at a High Level of Abstraction



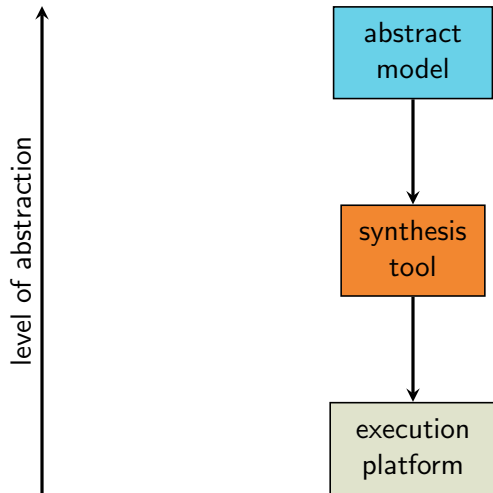
# Reality: Have to Implement at a Low Level of Abstraction



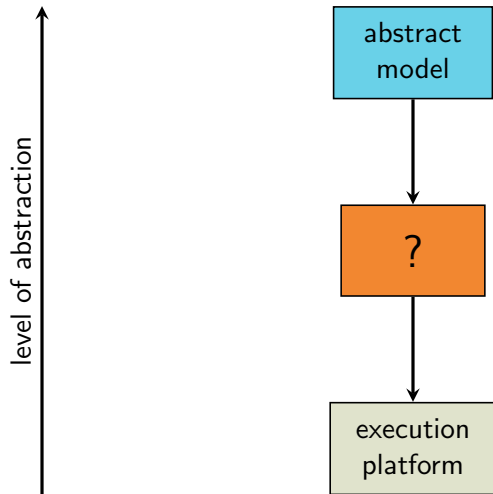
# Problem: How to Bridge the Gap?



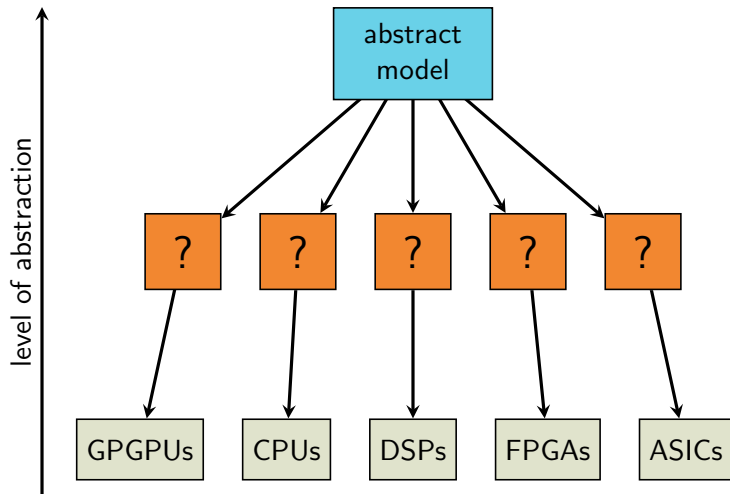
## Solution: Use Automated Synthesis Tools



# New Problem: How to Build Such a Tool?

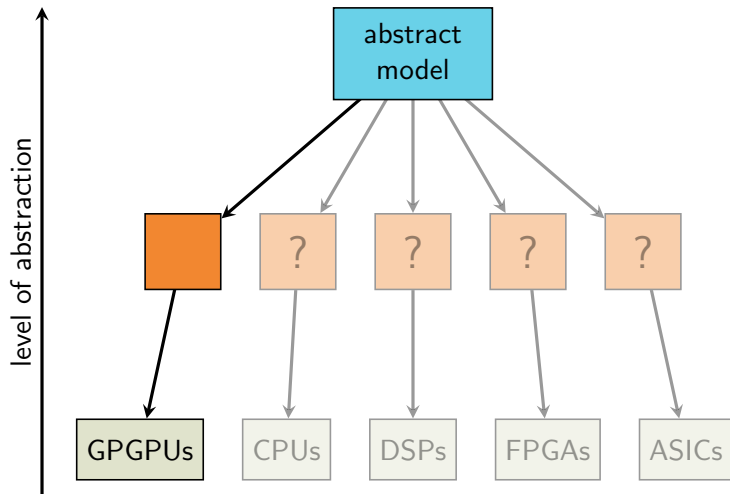


# New Problem: Different Challenges for Different Platforms





# This Talk: A Synthesis Tool for GPGPUs



# Outline

- ▶ Background
  - ▶ GPGPUs
  - ▶ ForSyDe
- ▶ Our ideas and synthesis tool (f2cc)
- ▶ Experiments
- ▶ Summary

# What Are GPGPUs?

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- ▶ *General-Purpose Graphics Processing Unit*

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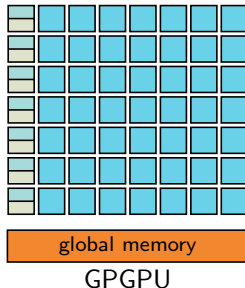
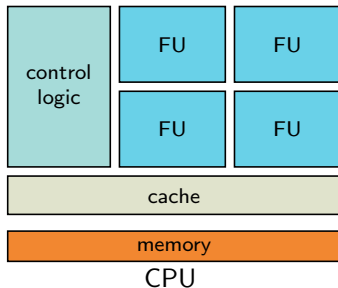
- ▶ *General-Purpose Graphics Processing Unit*
- ▶ Massively parallel, throughput-oriented platform

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- ▶ *General-Purpose Graphics Processing Unit*
- ▶ Massively parallel, throughput-oriented platform
- ▶ Can yield tremendous speedup for data-parallel programs
- ▶ Comparison between CPUs and GPGPUs:



# How to Use GPGPUs?

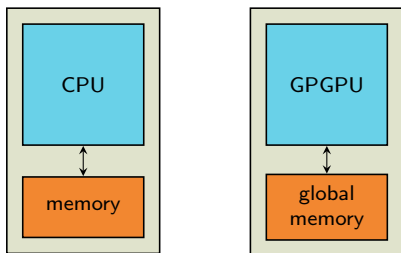


# How to Use GPGPUs?

- ▶ Programmed using C dialect (here assuming *CUDA C*)

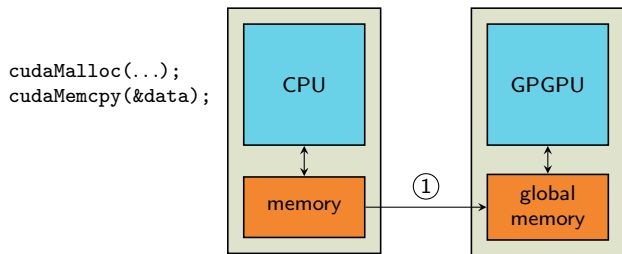
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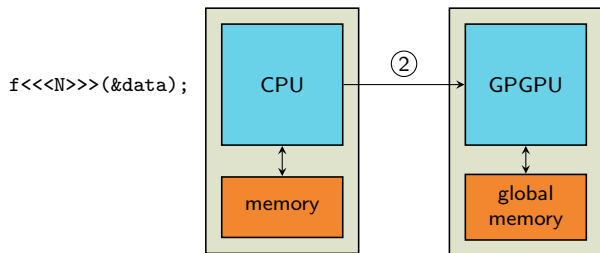
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Copy input data

# How to Use GPGPUs?

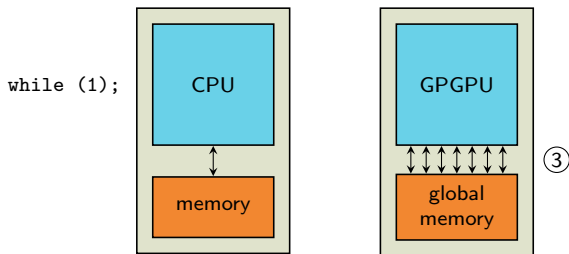
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Tell GPGPU to execute function  $f$  on input data, using  $N$  threads

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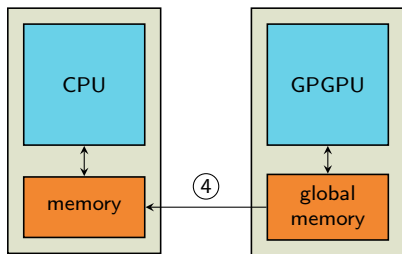


Wait until all threads have finished

# How to Use GPGPUs?

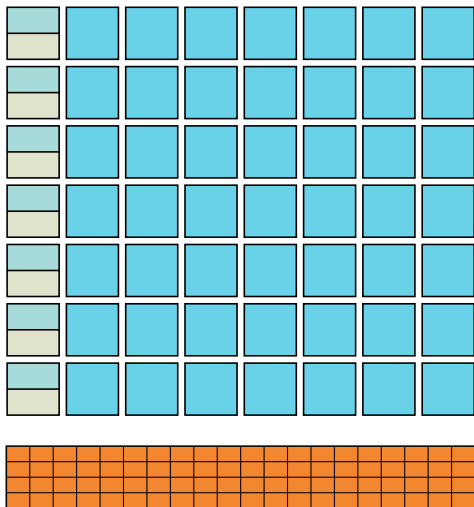
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```
cudaMemcpy(&res);  
cudaFree(...);
```

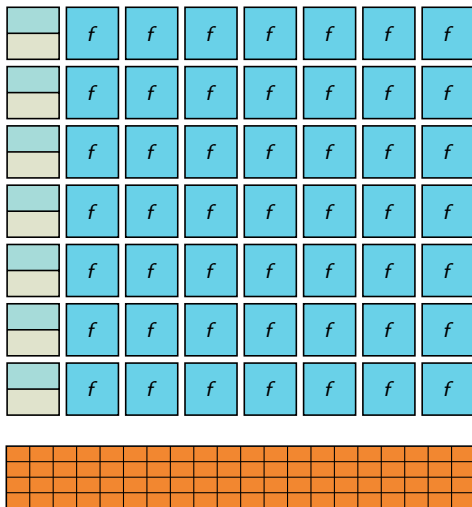


Copy result

# Inside the GPGPU During Execution

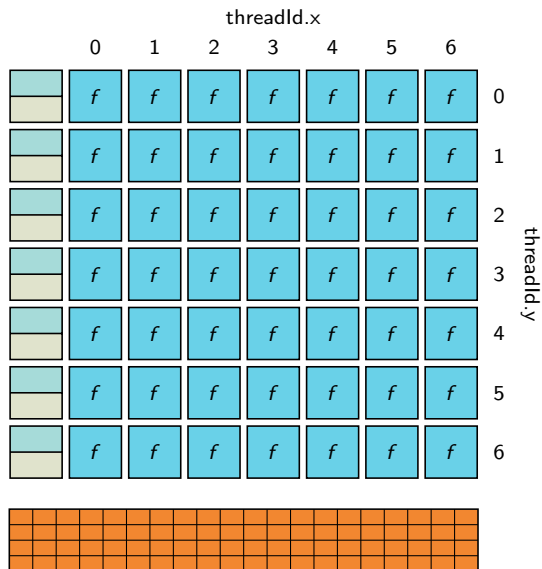


# Every Thread Executes the Same $f$

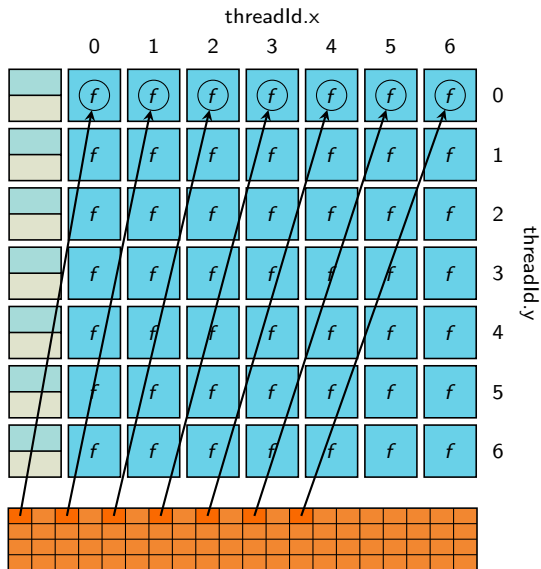




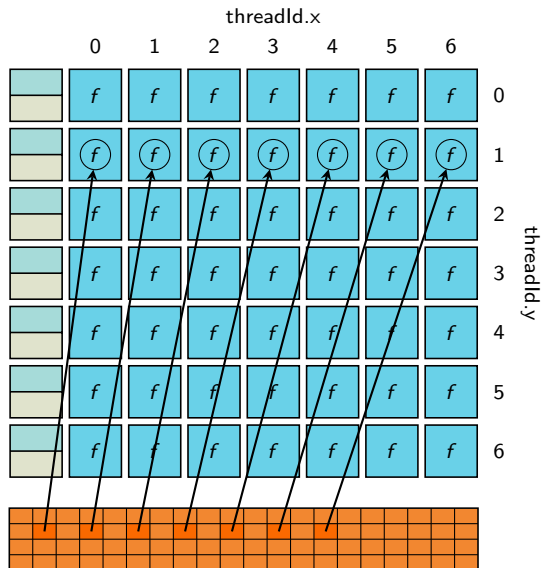
# Each Thread Has a Unique *Thread ID*



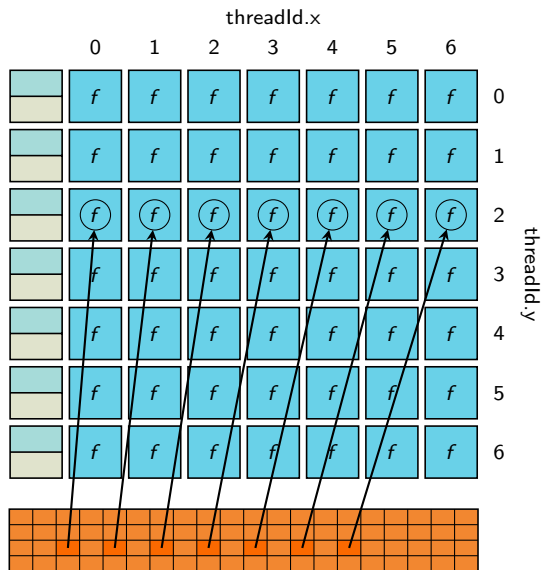
# $f$ Uses Thread ID to Determine What Data to Read



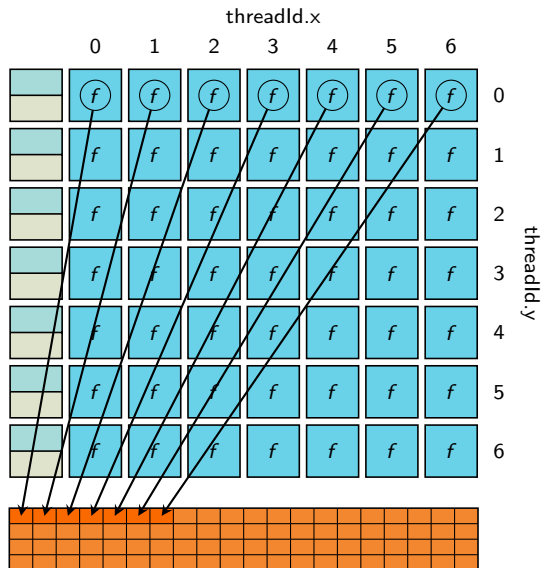
# $f$ Uses Thread ID to Determine What Data to Read



# *f* Uses Thread ID to Determine What Data to Read



# $f$ Uses Thread ID to Determine Where to Write Results



# Requirements for Optimal Performance

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- ▶ Abundance of data parallelism to offset GPGPU overhead (due mainly for data copying)
- ▶ High Computation-to-Global Memory Traffic Ratio
  - ▶ Often requires efficient use of various resources (like *shared memory*)
- ▶ No resource over-use

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- ▶ Complex data indexing schemes
- ▶ Performance depends on many interconnected factors

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- ▶ A formal modeling methodology



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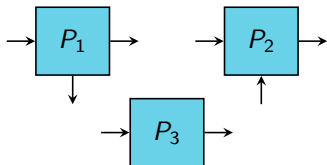
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- ▶ *Formal System Design*
- ▶ A formal modeling methodology
  - ▶ Uses the theory of *Models of Computation (MoCs)*
  - ▶ Captures behavior of heterogeneous embedded systems as *ForSyDe models*

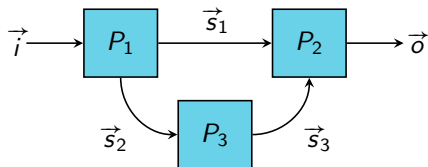
# What Is a ForSyDe Model?

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A ForSyDe model is a *concurrent network* of *processes* . . .

# What Is a ForSyDe Model?

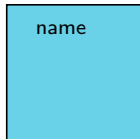


... that communicate via *signals*.

# What Is a Process Constructor?

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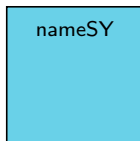
process constructor



A process constructor is a *template* . . .

# What Is a Process Constructor?

process constructor

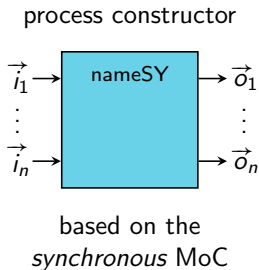


based on the  
*synchronous* MoC

... that is *based* on a specific model of computation, ...

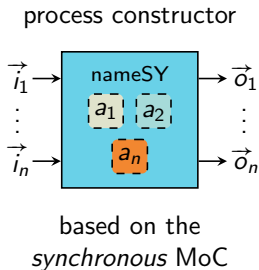


# What Is a Process Constructor?



... has a number of declared *input* and *output signals*, ...

# What Is a Process Constructor?

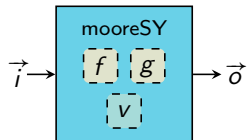


... and takes zero or more *side effect-free arguments*.

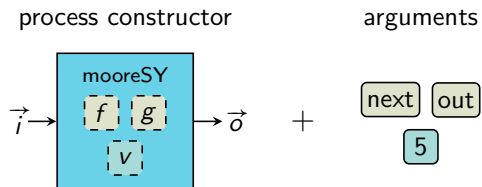
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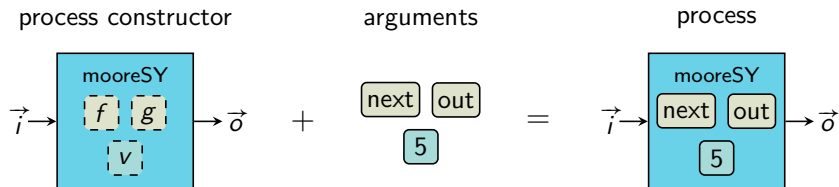
process constructor



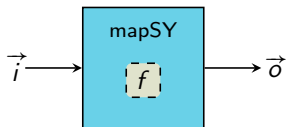
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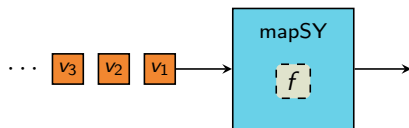
# Creating a Process



# The MapSY Process Constructor

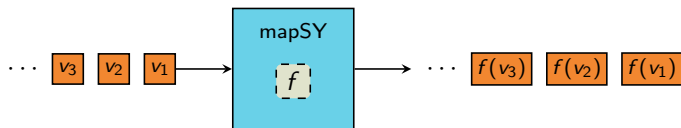


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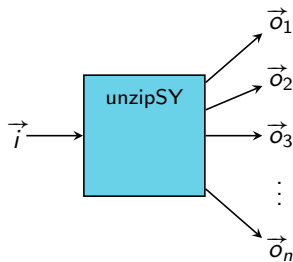




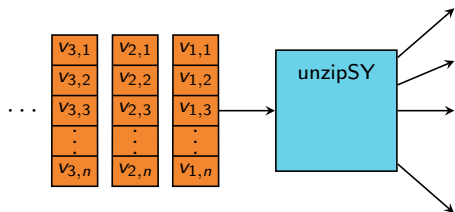
# The MapSY Process Constructor



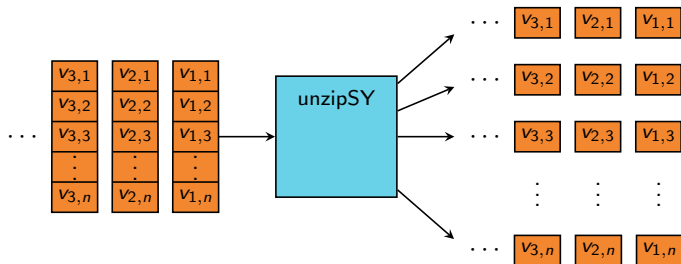
# The UnzipSY Process Constructor



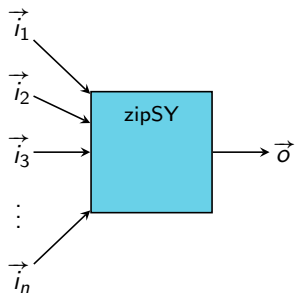
# The UnzipSY Process Constructor



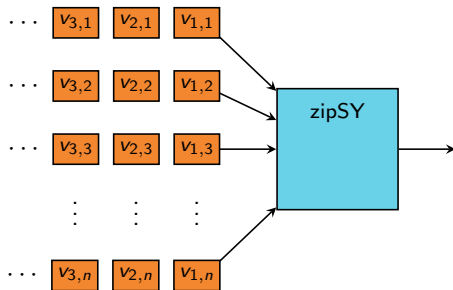
# The UnzipSY Process Constructor



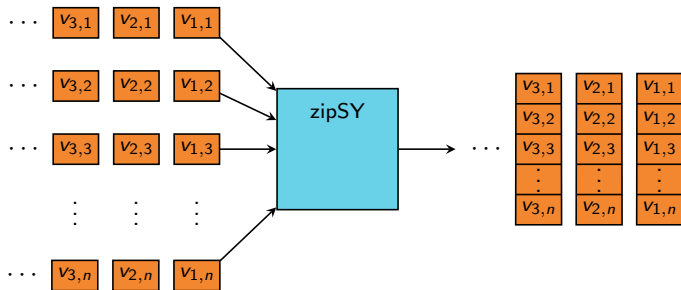
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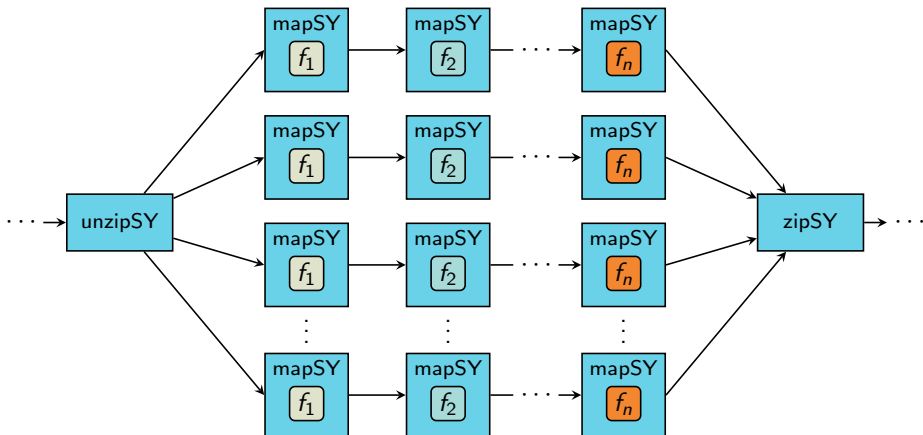
# The ZipSY Process Constructor



# ForSyDe Models Suitable for GPGPUs?

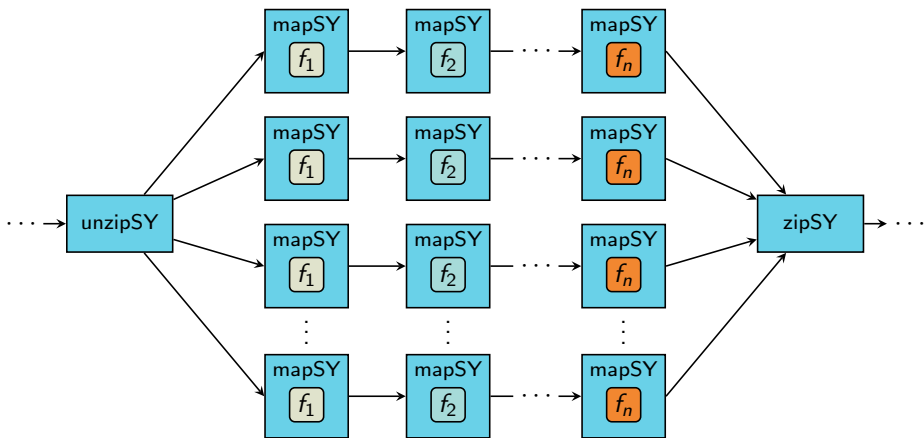


# ForSyDe Models Suitable for GPGPUs?

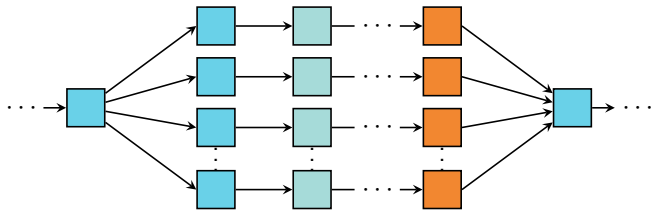


The *split-map-merge* pattern

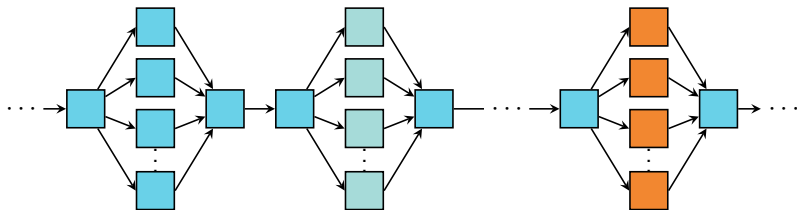
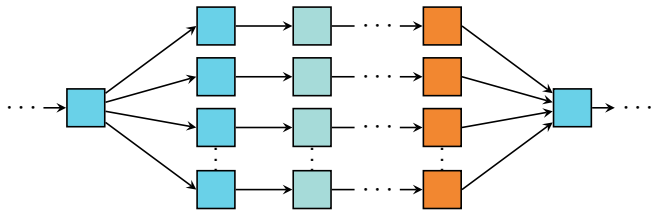
# Want to Handle Only One Function



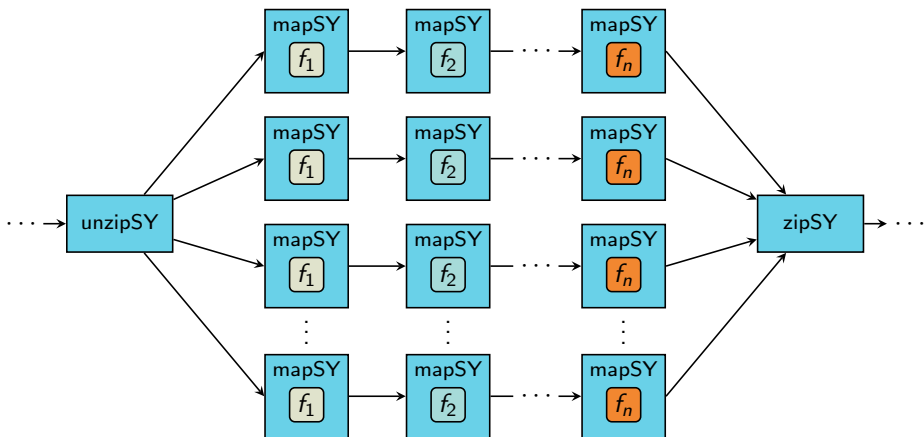
## Method 1: *Section Splitting*



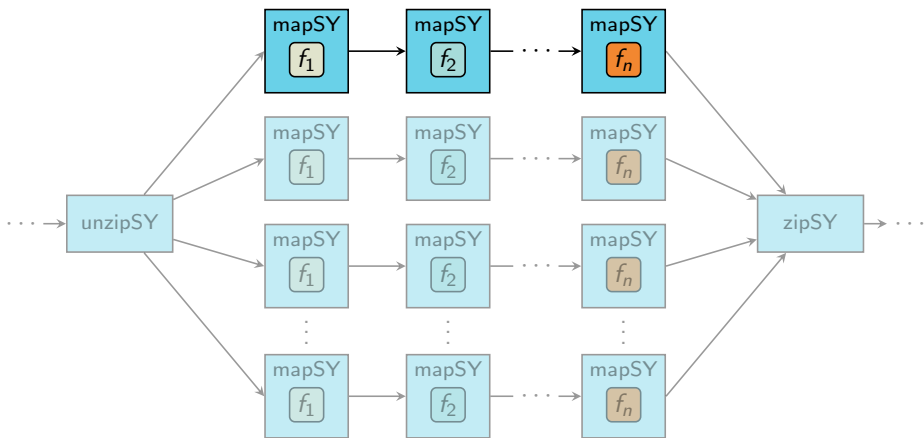
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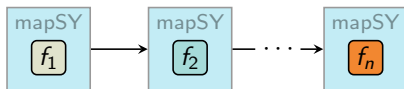
## Method 2: *Process Coalescing*



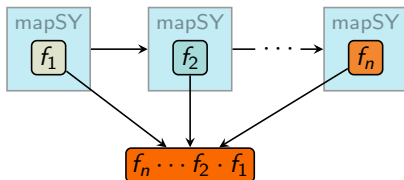
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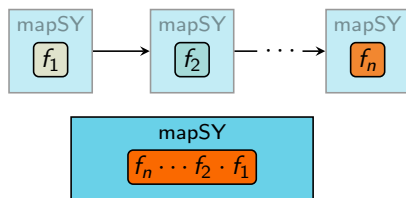


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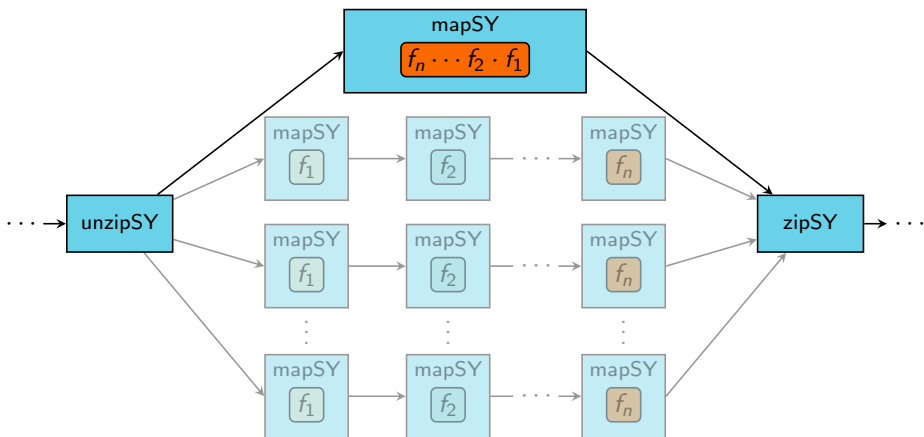




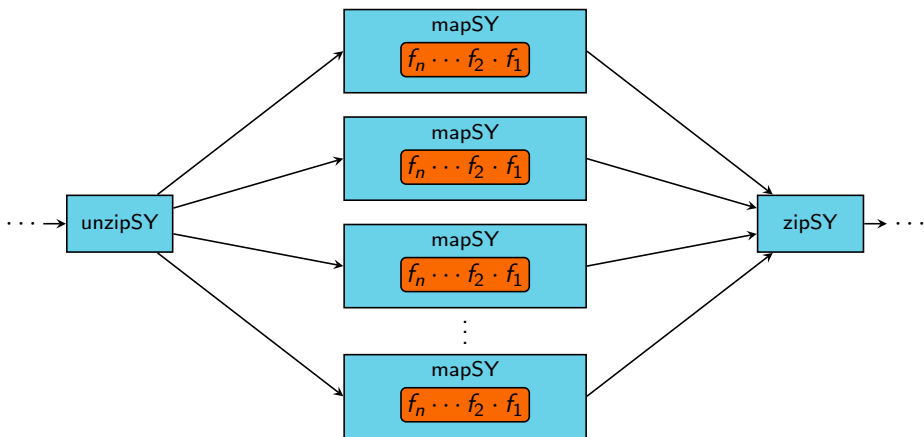
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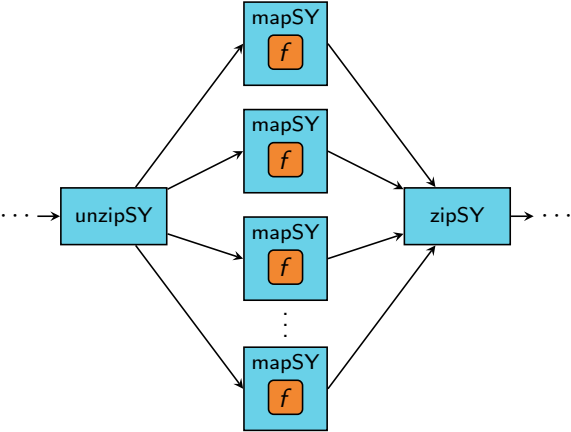
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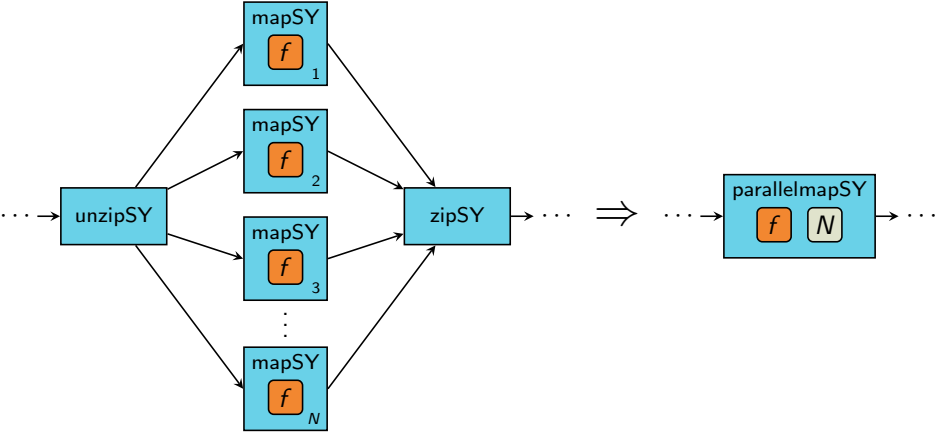
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# Fuse Zip-Map-Unzip Structures Into *ParallelMaps*



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# Synthesis

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- ▶ ParallelmapSY processes:

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- ▶ ParallelmapSY processes:
  - ▶ Choose C or CUDA C implementation



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f2cc

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- ▶ *ForSyDe-2-CUDA C*

# f2cc

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- ▶ Proof-of-concept synthesis tool

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  1. All functions are written in C



# f2cc

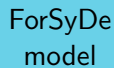
- ▶ *ForSyDe-2-CUDA C*
- ▶ Proof-of-concept synthesis tool
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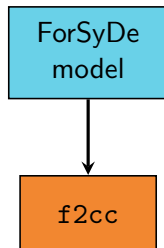
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ForSyDe  
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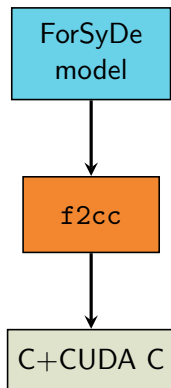
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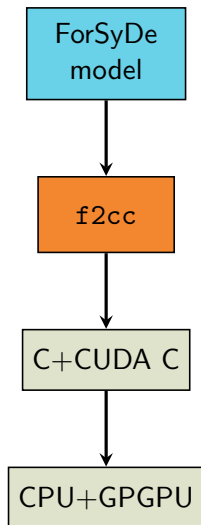
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  3. Get implementation in C+CUDA C



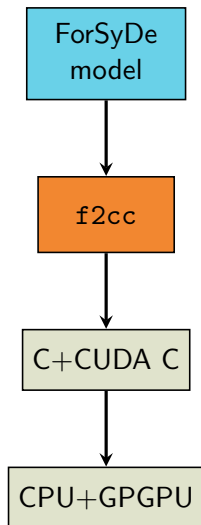
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  4. Compile and execute



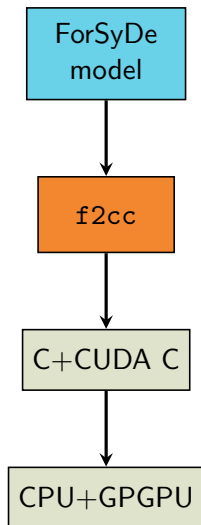
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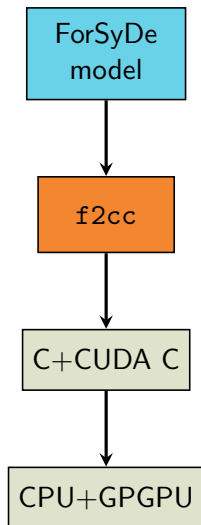
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  - ▶ Process scheduling





# f2cc

- ▶ *ForSyDe-2-CUDA C*
- ▶ Proof-of-concept synthesis tool
- ▶ Assumptions:
  1. All functions are written in C
  2. All processes are based on synchronous MoC
- ▶ Design flow:
  1. Design ForSyDe model
  2. Run f2cc on ForSyDe model
  3. Get implementation in C+CUDA C
  4. Compile and execute
- ▶ Other aspects in paper but not in talk:
  - ▶ Process scheduling
  - ▶ Signal management



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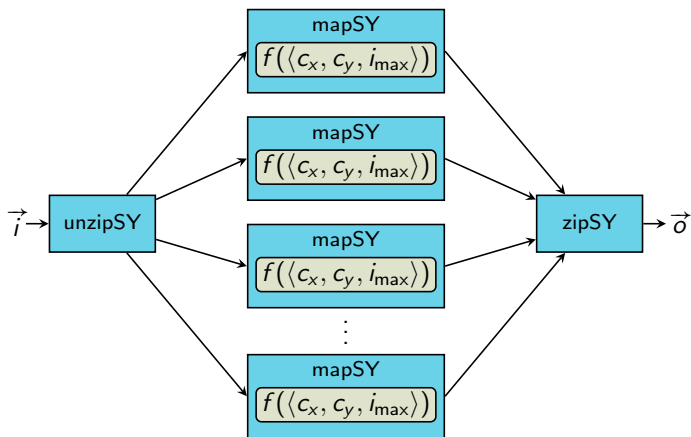
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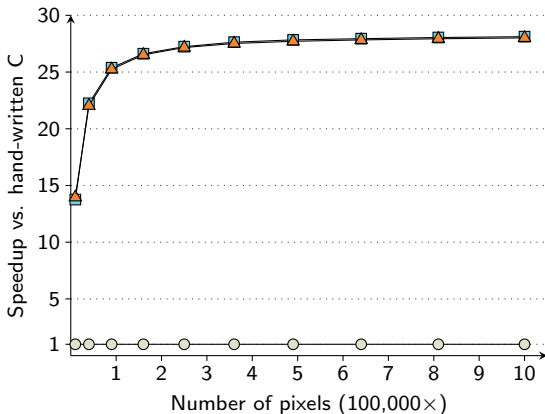
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    - ▶  $\sim 30\times$  speedup is good

# ForSyDe Model of Mandelbrot Application

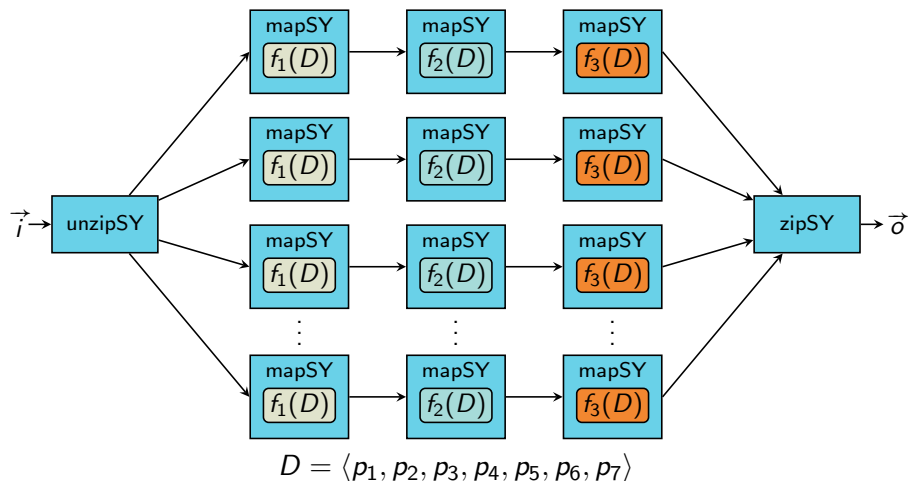


# Achieve Expected Outcome for Mandelbrot Application

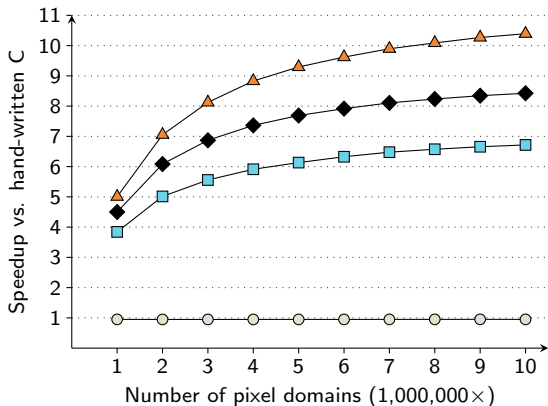


- Synthesized C
- Synthesized C + CUDA C (no shared memory)
- △ Synthesized C + CUDA C (using shared memory)

# ForSyDe Model of Image Processing Application



# Achieve Expected Outcome for Image Processing Application



- Synthesized C
- Synthesized C + CUDA C (section splitting, no shared memory)
- ▲ Synthesized C + CUDA C (process coalescing, no shared memory)
- ◆ Synthesized C + CUDA C (process coalescing, with shared memory)



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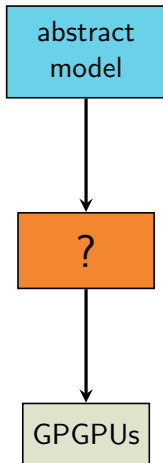
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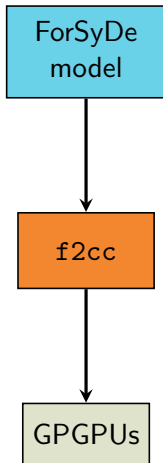
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- ▶ Eager memory-copying scheme
  - ▶ Reduce overhead through lazy copying

# Summary

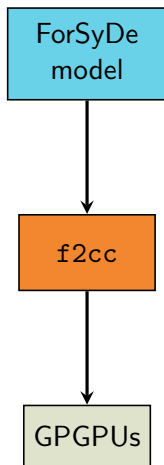
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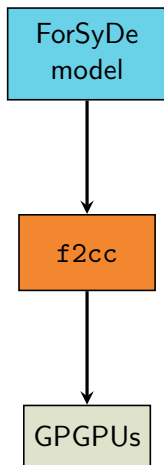
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- ▶ Get high-performance implementation for supported design pattern



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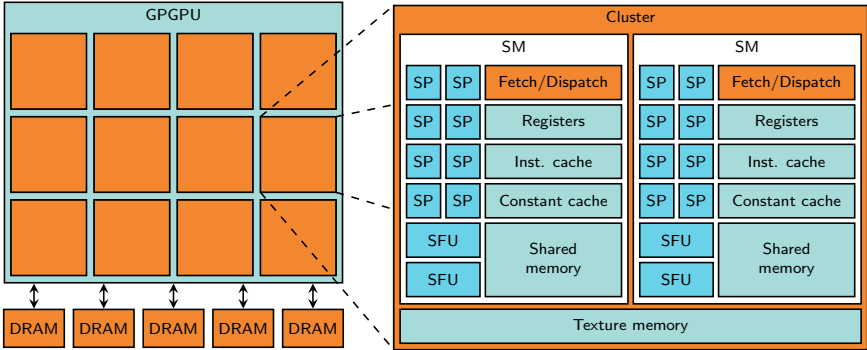


- Get high-performance implementation for supported design pattern

f2cc available at:

<https://forsyde.ict.kth.se/trac/wiki/ForSyDe/f2cc>

# NVIDIA's GPGPU Architecture



```
<graphml>
  <graph id="test" edgedefault="directed">
    ...
    <node id="unzip"> ... </node>
    <node id="zip"> ... </node>
    <node id="map1">
      <data key="process_type">mapSY</data>
      <data key="procfun_arg">
        int f1(int x) { return x + 1; }
      </data>
      <port name="in" /><port name="out" />
    </node>
    <node id="map6">
      <data key="process_type">mapSY</data>
      <data key="procfun_arg">
        int f2(int x) { return x * 2; }
      </data>
      <port name="in" /><port name="out" />
    </node>
    <edge source="unzip" sourceport="out1" target="map1"
          targetport="in" />
    <edge source="map1" sourceport="out" target="map4"
          targetport="in" />
    ...
  </graph>
</graphml>
```

# Function Produced From Process Coalescing

```
__device__  
int f12(int x) {  
    int res_f1 = f1(x);  
    int res_f2 = f2(res_f1);  
    return res_f2;  
}
```

## Kernel Function Produced (Without Shared Memory)

```
__global__
void f12_kernel(
    const int* input,
    int* output,
    int offset)
{
    unsigned int global_index =
        (blockIdx.x * blockDim.x + threadIdx.x) + offset;

    if (global_index < 3) {
        int input_index = global_index * 1;

        output[global_index] = f12(input[input_index]);
    }
}
```

## Kernel Function Produced (With Shared Memory)

```
__global__
void f12_kernel(
    const int* input,
    int* output,
    int offset)
{
    unsigned int global_index =
        (blockIdx.x * blockDim.x + threadIdx.x) + offset;
    extern __shared__ int input_cached[];
    if (global_index < 3) {
        int input_index = threadIdx.x * 1;
        int gi_index = global_index * 1;
        input_cached[input_index + 0] = input[gi_index + 0];
        output[global_index] = f12(input_cached[input_index]);
    }
}
```

## Produced Invoker Function (1 of 3)

```
void f12_invoker(const int* input, int* output) {
    int* device_input;
    int* device_output;

    struct cudaDeviceProp prop;
    cudaGetDeviceProperties(&prop, 0);

    int tlimit = prop.maxThreadsPerBlock *
                 prop.multiProcessorCount;

    cudaMalloc((void**) &device_input, 3 * sizeof(int));
    cudaMalloc((void**) &device_output, 3 * sizeof(int));
    cudaMemcpy((void*) device_input,
               (void*) input,
               3 * sizeof(int),
               cudaMemcpyHostToDevice);
}
```

## Produced Invoker Function (2 of 3)

```
if (prop.kernelExecTimeoutEnabled) {
    int num_t_left = 3;
    int offset = 0;
    while (num_t_left > 0) {
        int num_t_exec =
            num_t_left < tlimit ? num_t_left : tlimit;
        KernelConfig c = calculateBestKernelConfig(...);
        f12_kernel<<<c.grid, c.threadBlock, c.sharedMemory>>>
            (device_input, device_output, offset);
        int num_t_exed = c.grid.x * c.threadBlock.x;
        num_t_left -= num_t_exed;
        offset += num_t_exed;
    }
}
else {
    KernelConfig c = calculateBestKernelConfig(...);
    f12_kernel<<<c.grid, c.threadBlock, c.sharedMemory>>>
        (device_input, device_output, 0);
}
```



## Produced Invoker Function (3 of 3)

```
    cudaMemcpy((void*) output,  
              (void*) device_output,  
              3 * sizeof(int),  
              cudaMemcpyDeviceToHost);  
    cudaFree((void*) device_input);  
    cudaFree((void*) device_output);  
}
```