Methodology for mapping image processing algorithms on massively parallel processors

An NVIDIA GPU specific approach

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French community of compilation – 12th meeting – Saint Germain au Mont d'Or

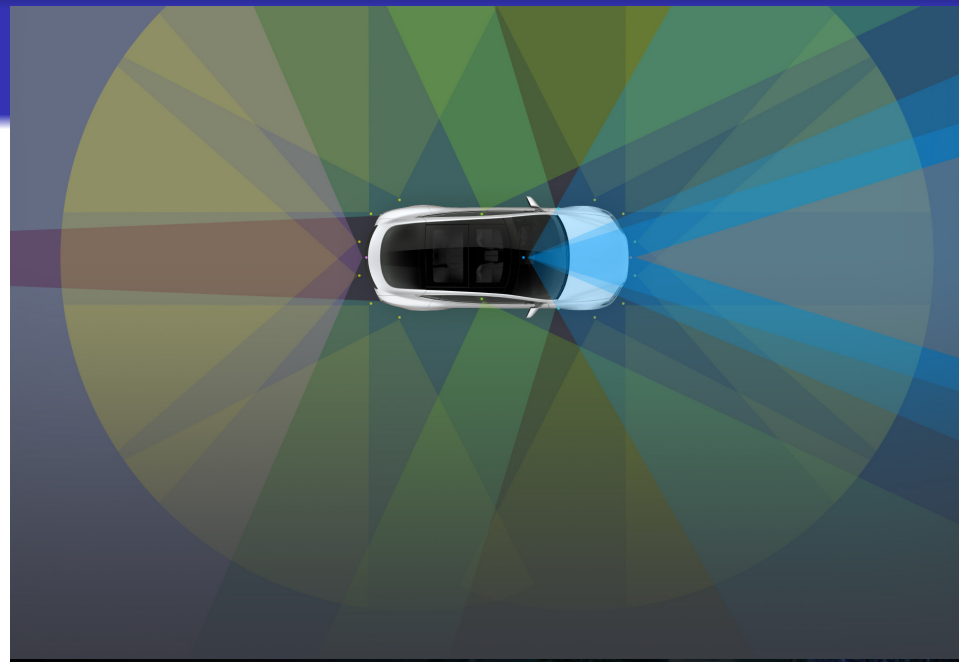
Image processing domain

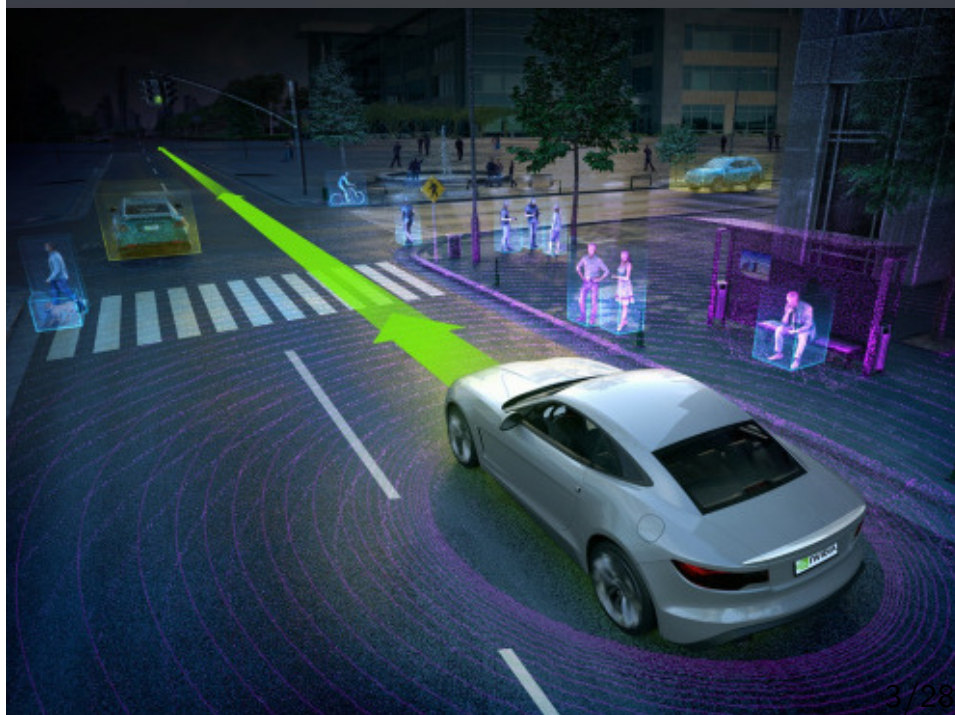
Figure: Image processing examples

Image processing domain

General tendances for today and tomorrow:

- Data source volume is **growing exponentially**
- Data sources tend to be **multiplied**
- Available computing time tends to be **shorter** for real time processing
- Image processing algorithms are even **more complex**





Architectural evolution

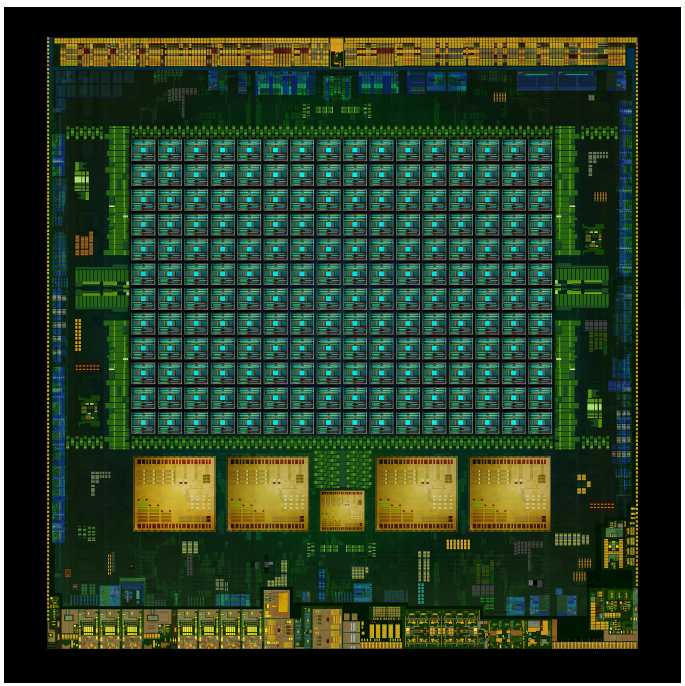


Figure: NVIDIA Kepler processor – 192 cores architecture

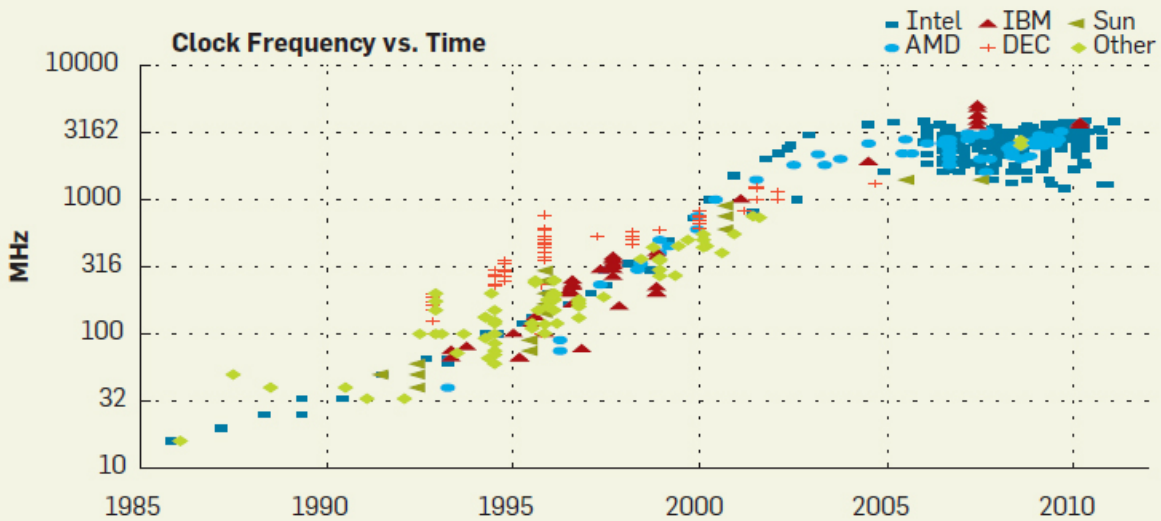


Figure: Processor frequency wall

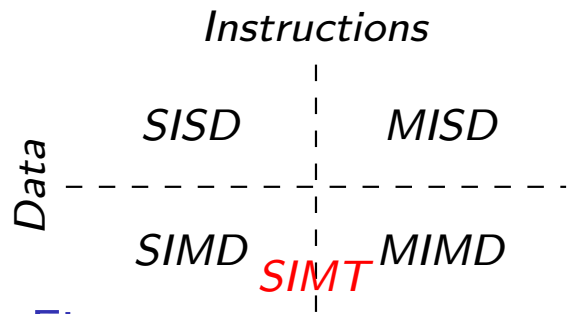


Figure: Flynn's taxonomy

Why do we need a methodology?

Parallel thinking is not trivial. The following methodology has been elaborated to provide:

- an assistance for GPU developpers,
- an improvement of software production for industries,
- a support for other domain engineers,
- an assistance to optimise software for a specific GPU architecture.

Tools and compilers results can be limited in some cases:

- dynamic control code
- intensive function calls
- pointers arithmetic
- object oriented languages
- ...

Content

Content

Content

Content

Optical Flow: definition

Principle:

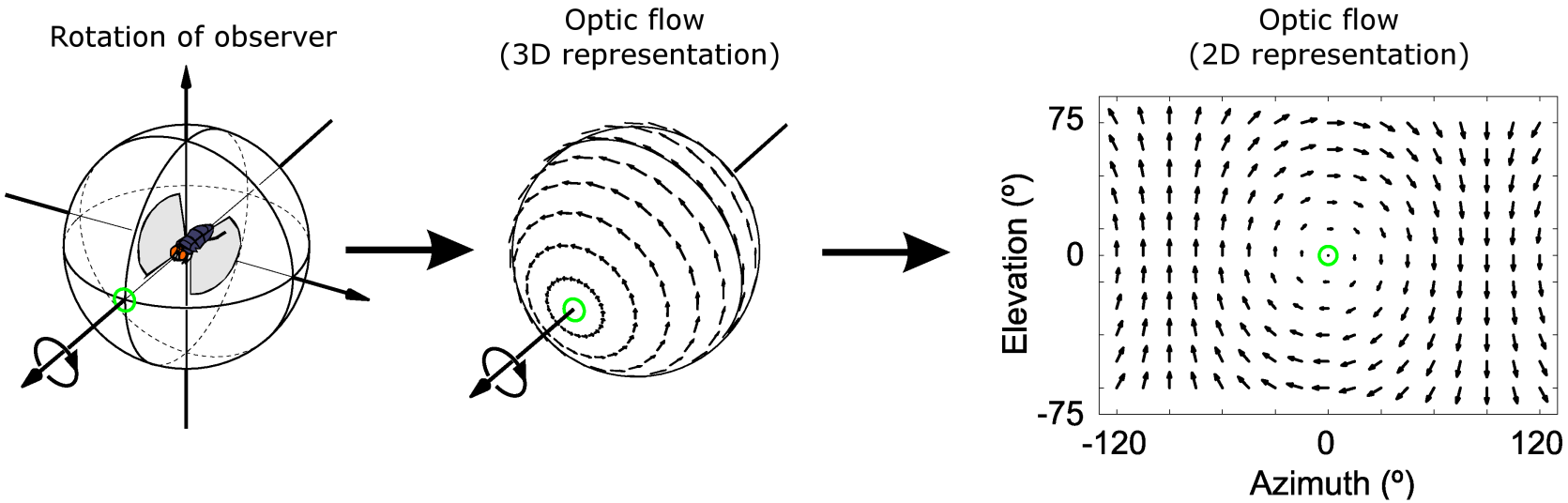
Motion quantification of each pixel taken from two distinct pictures.

Image processing application:

- spatial characterization
- temporal characterization

Examples of applications:

- Motion estimation
- Image stabilization
- Image segmentation
- Moving object tracking
- SLAM algorithms
- ...



Optical Flow: industrial application example

Figure: Example of motion flow analysis. Tesla Motor Company automatic drive.

Algorithm data

The SimpleFlow[1] algorithm is available in the OpenCV extensions.

- Approximatively 600 lines of code
- Sequential algorithm
- Dynamic control code
- Approximative runtime for a couple of 2 million pixels images:
  - **200s** on a NVIDIA Jetson TX1
    - ARM Cortex A57(1.9GHz) + A53(1.3GHz)
  - **50s** on a desktop computer
    - Intel Core I7 4770S (8 logical cores at 3.1GHz)
  - Ideal runtime: **40ms**
- Language and library: C++ with the OpenCV library

[1] Michael W. Tao et al. "SimpleFlow: A Non-iterative, Sublinear Optical Flow Algorithm". In: *Computer Graphics Forum (Eurographics 2012)* 31.2 (May 2012). URL: http://graphics.berkeley.edu/papers/Tao-SAN-2012-05/.

Simplified CallGraph

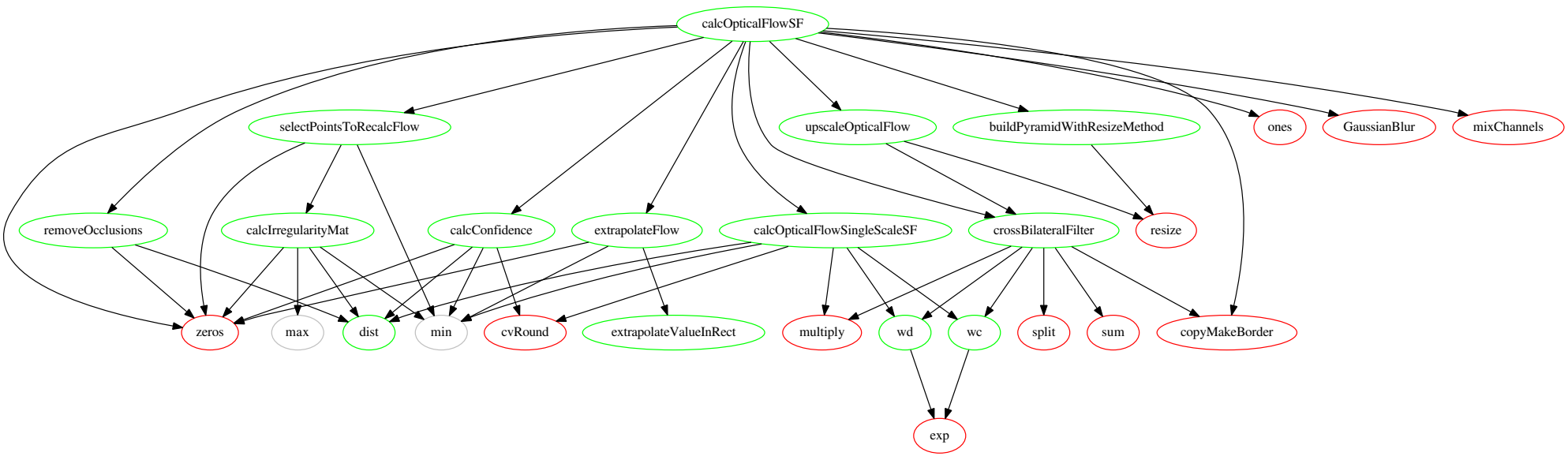


Figure: Simplified call graph. function is simpleflow one, function is openCV one and function comes from the C++ std library

Application example

Figure: Image 1 (t)

Figure: Image 2 ($t + \delta$)

Figure: X coordinate pixel motions

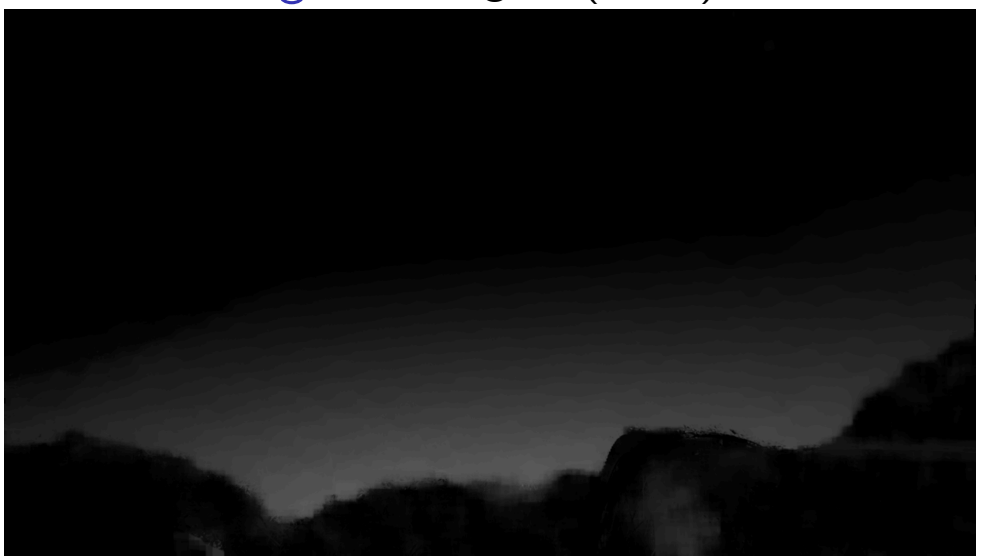
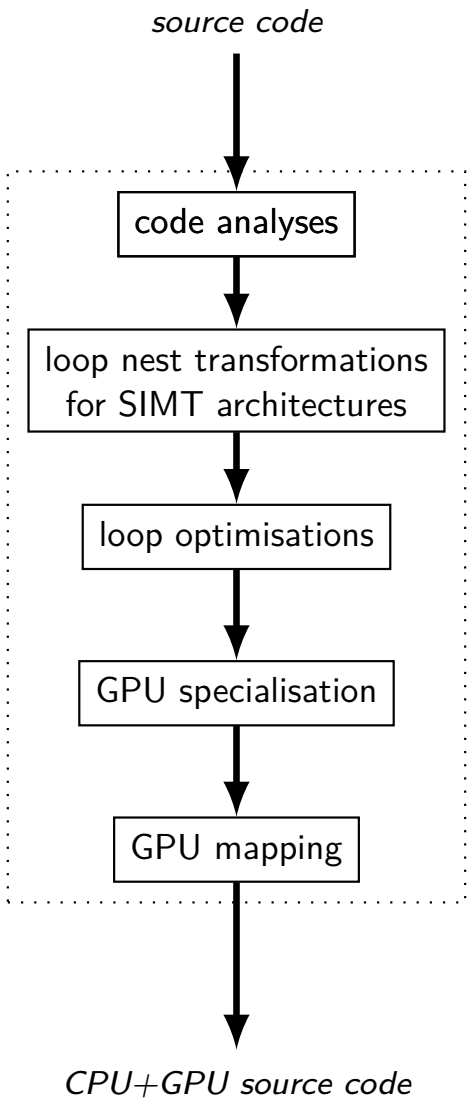


Figure: Y coordinate pixel motions


source code
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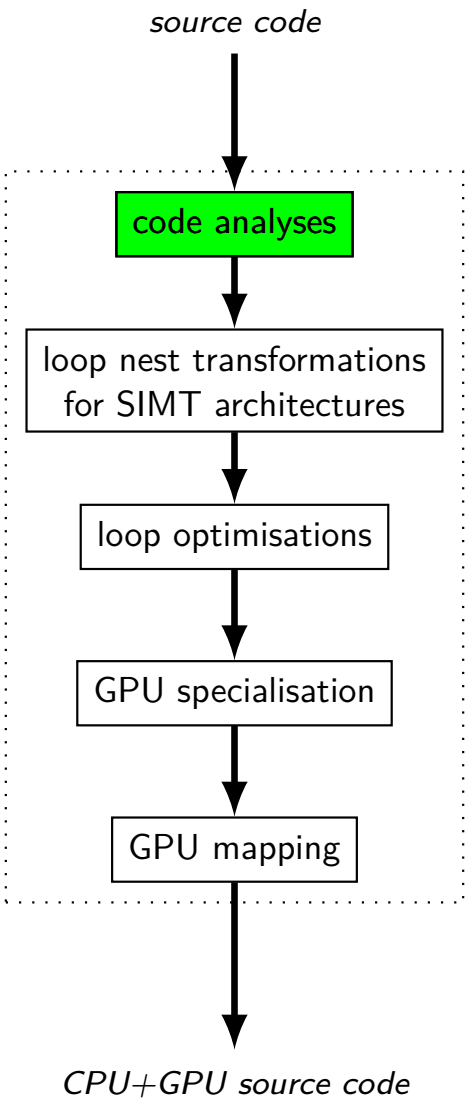
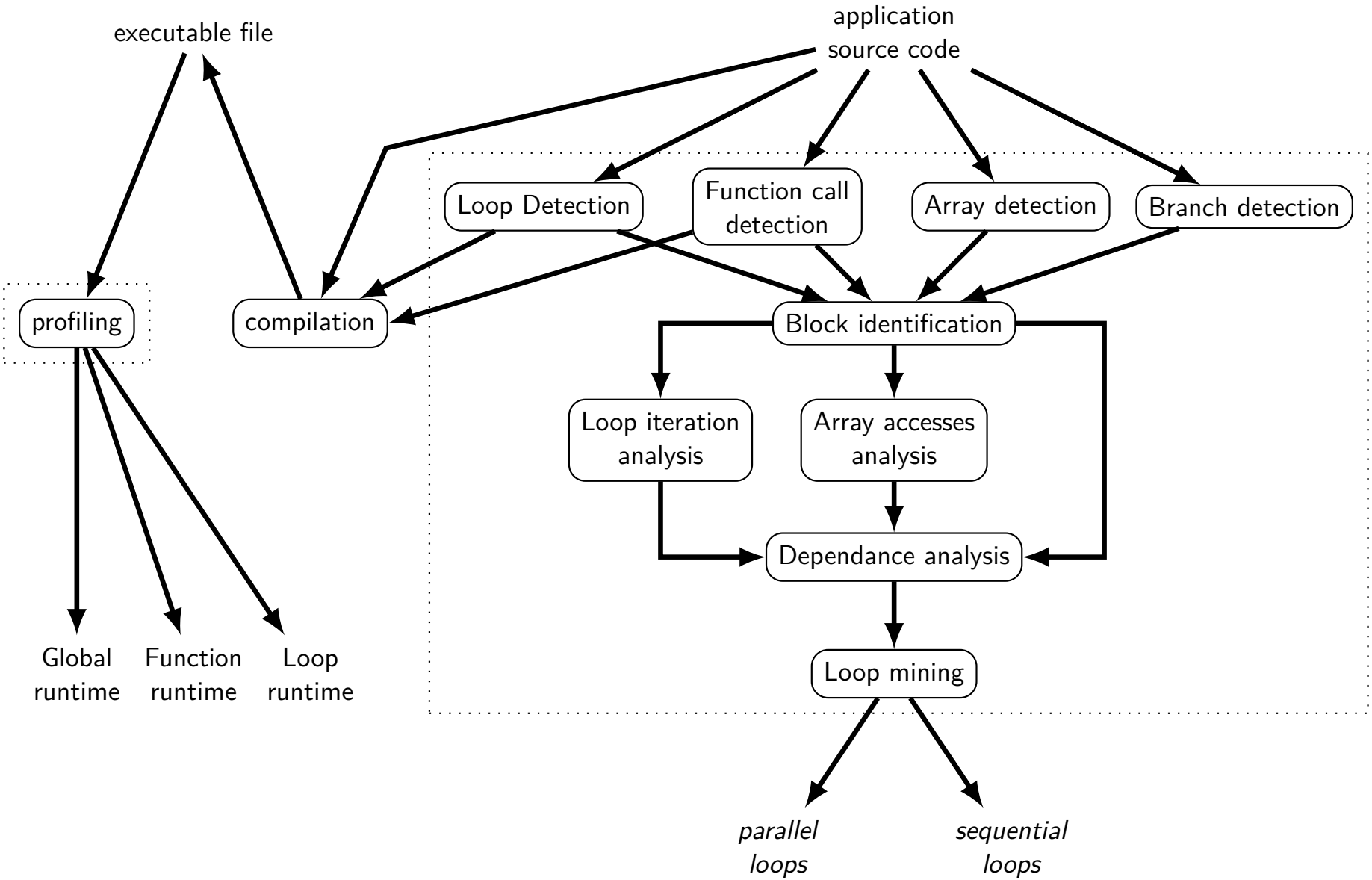
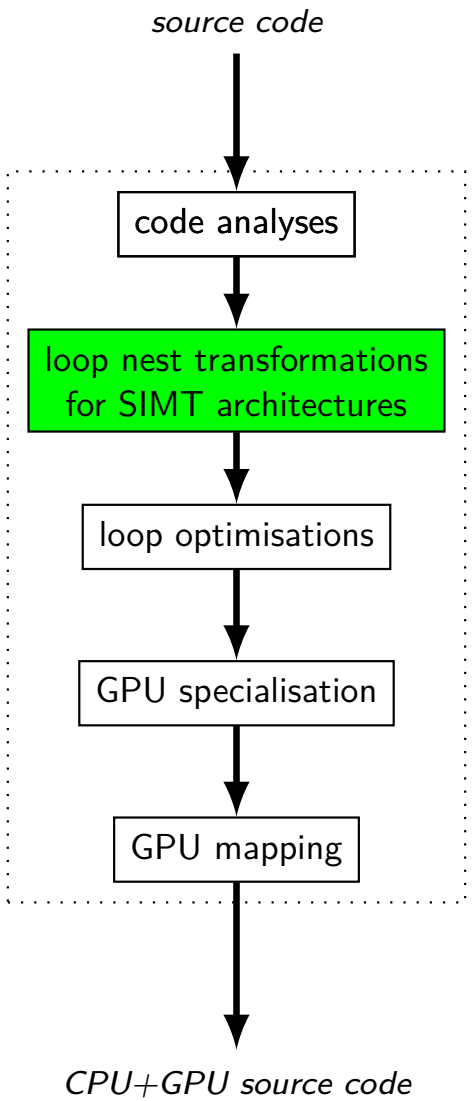
loop nest transformations for SIMT architectures
loop optimisations
GPU specialisation
GPU mapping
CPU+GPU source code

Code analyses




executable file
application source code
Loop Detection
Function call detection
Array detection
Branch detection
profiling
compilation
Block identification
Loop iteration analysis
Array accesses analysis
Dependance analysis
Loop mining
Global runtime
Function runtime
Loop runtime
parallel loops
sequential loops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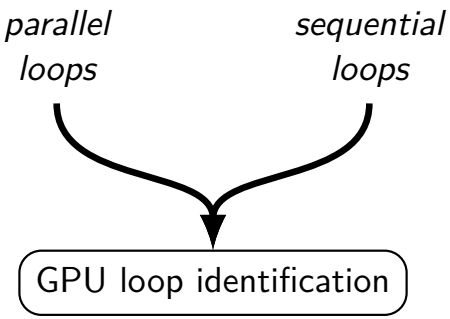
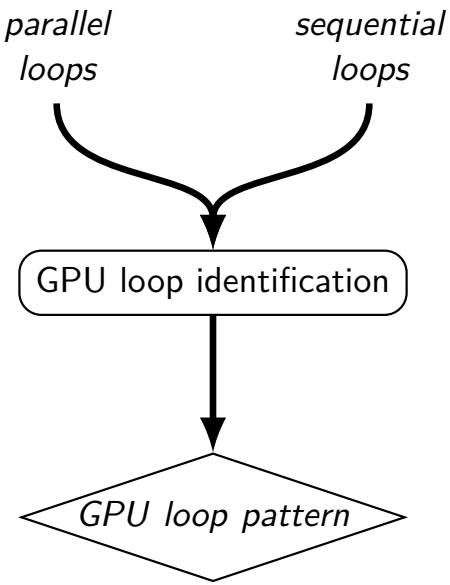
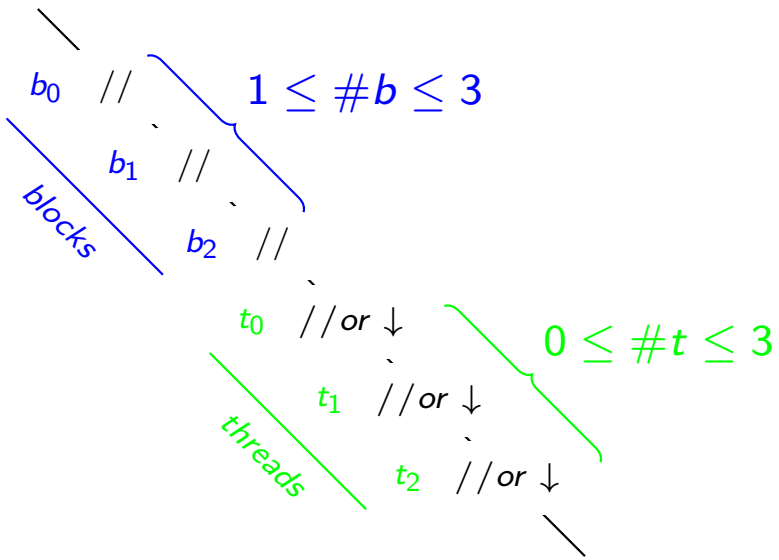
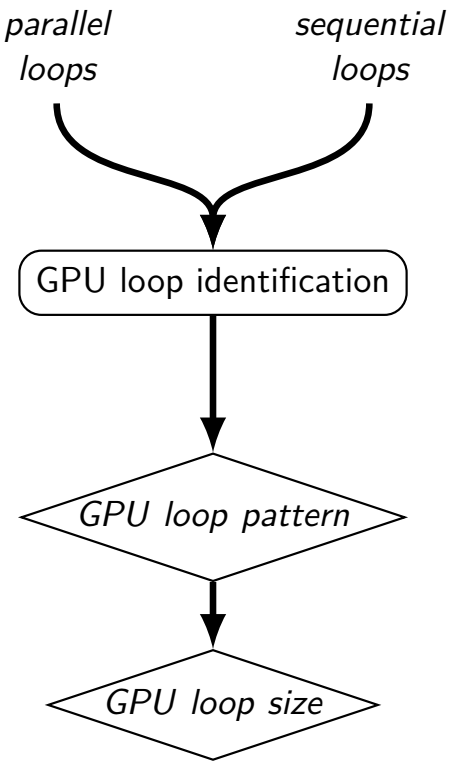

parallel loops
sequential loops
GPU loop identification

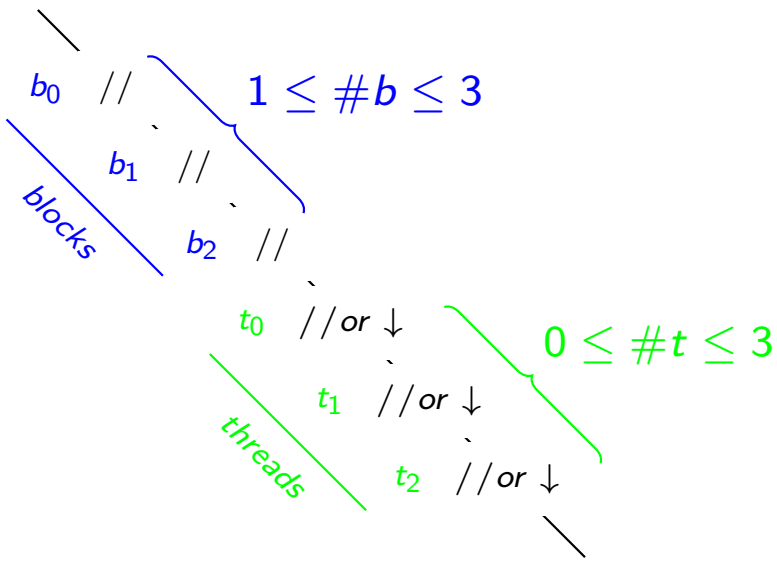


GPU loop pattern





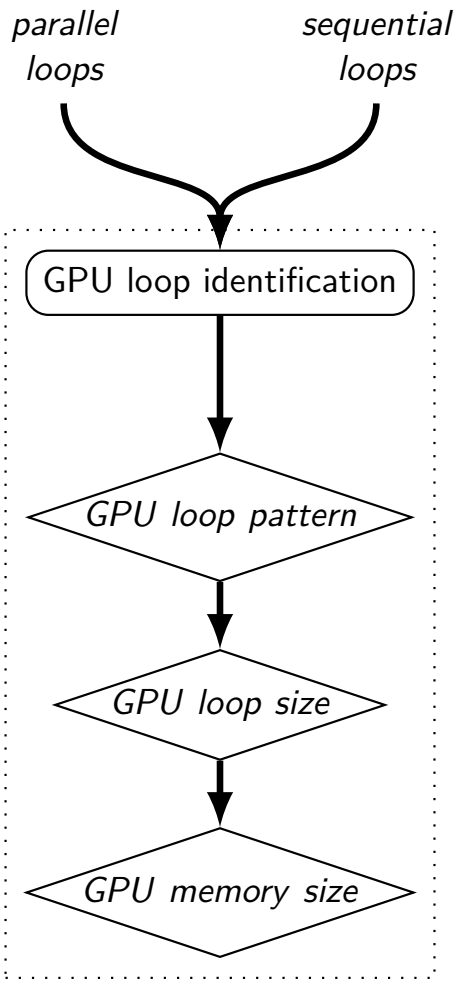
GPU loop pattern



GPU loop size

$$\begin{cases} b = b_0 \times b_1 \times b_2 \\ b_0 < 2147483647 \\ b_1 < 65535 \\ b_2 < 65535 \\ b \gg t \end{cases}$$

$$\begin{cases} t = t_0 \times t_1 \times t_2 \\ t < 1024 \\ t_0 < 1024 \\ t_1 < 1024 \\ t_2 < 64 \\ t\%32 = 0 \\ t > 4 \times 32 \end{cases}$$



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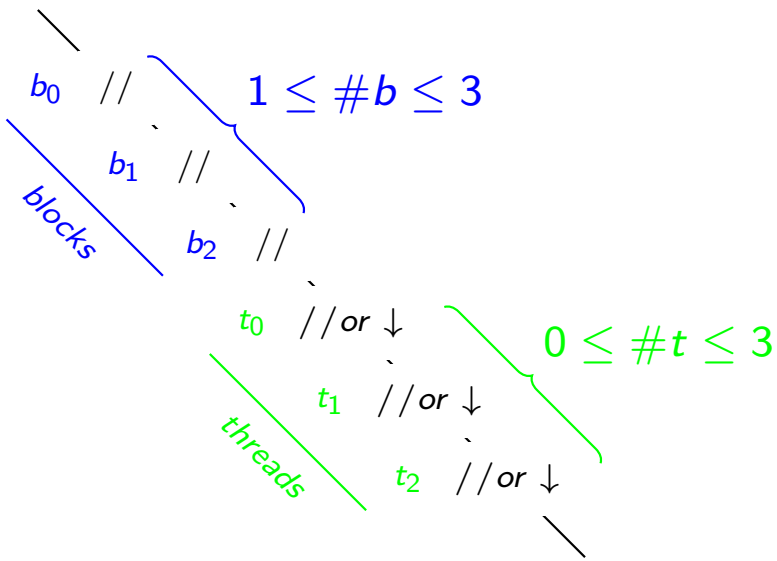

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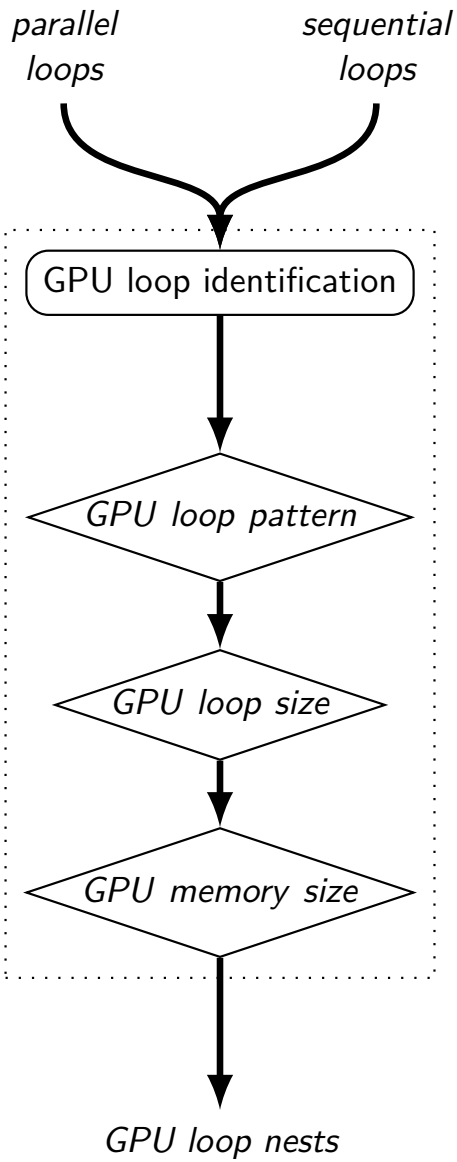
GPU memory size

$$Global\ memory_{footprint} < GPU_{memory}$$



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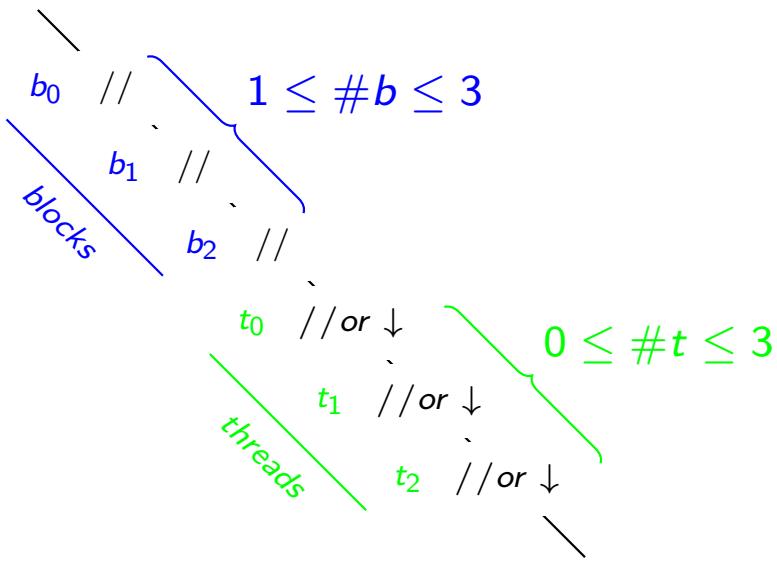

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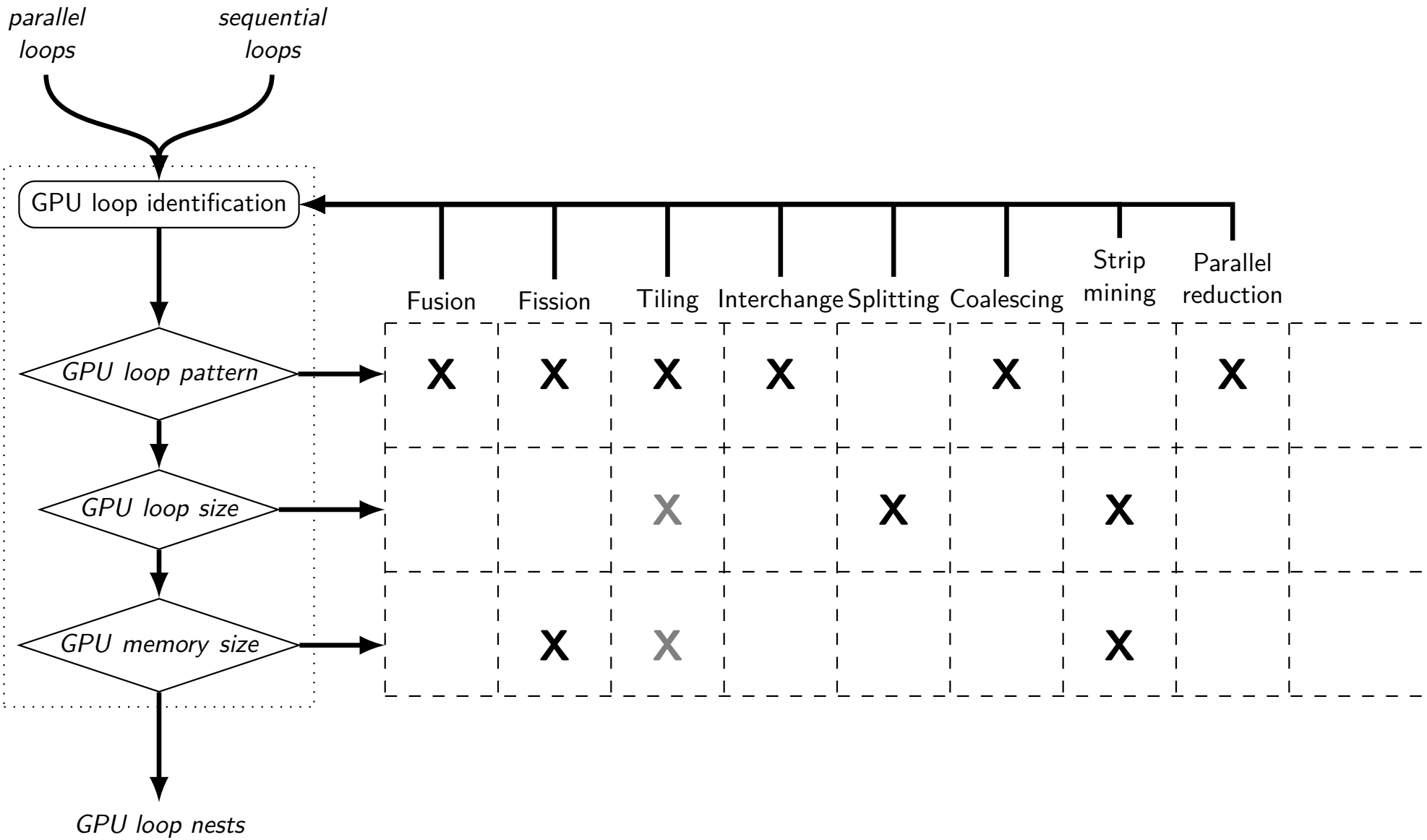
parallel loops
sequential loops
GPU loop identification
GPU loop pattern
GPU loop size
GPU memory size
GPU loop nests
Fusion
Fission
Tiling
Interchange
Splitting
Coalescing
Strip mining
Parallel reduction
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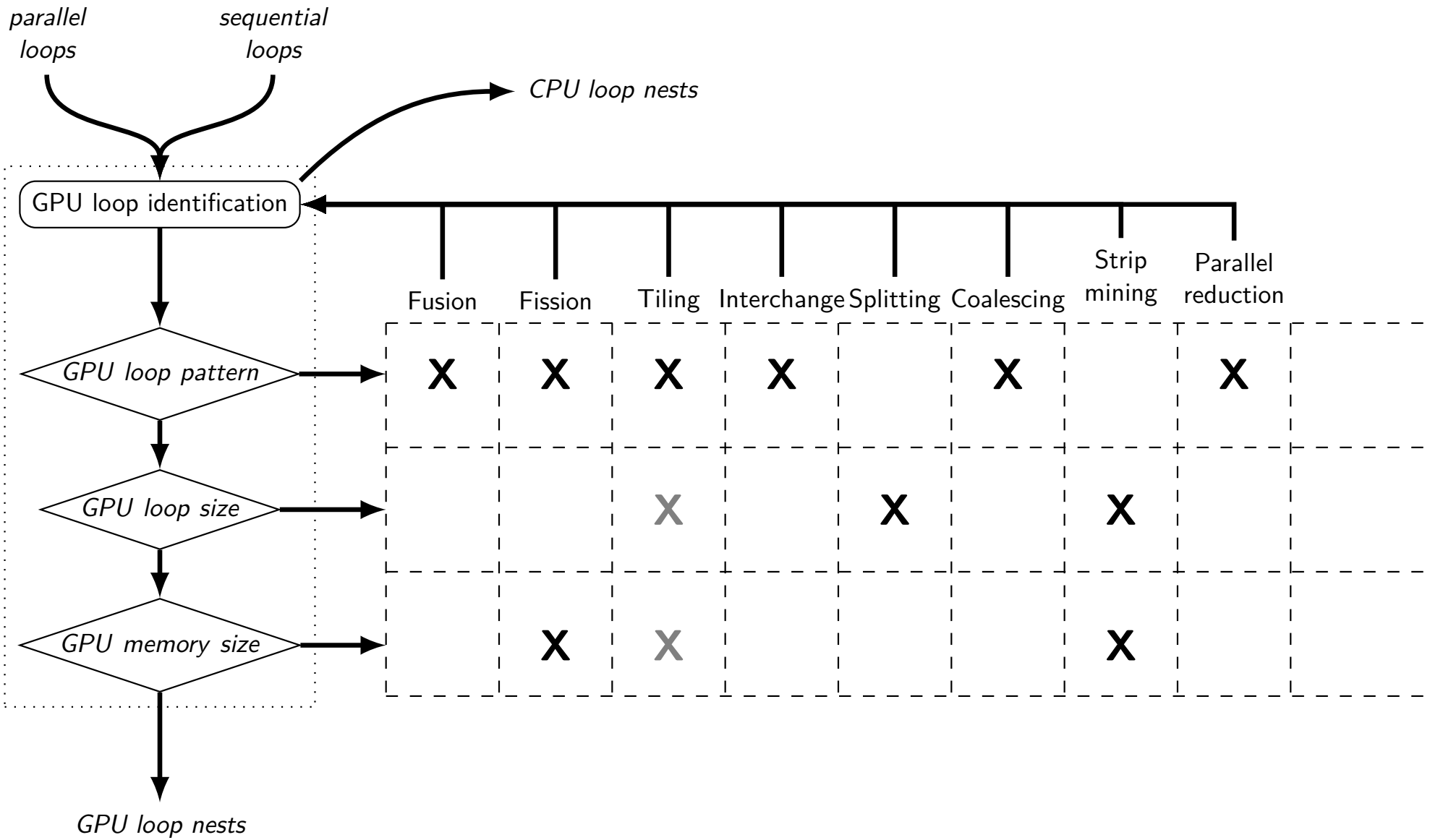
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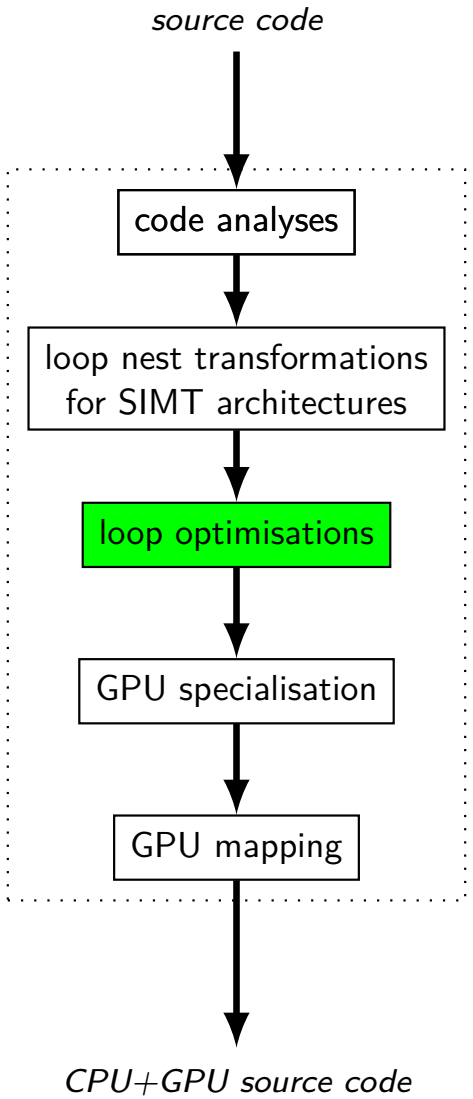
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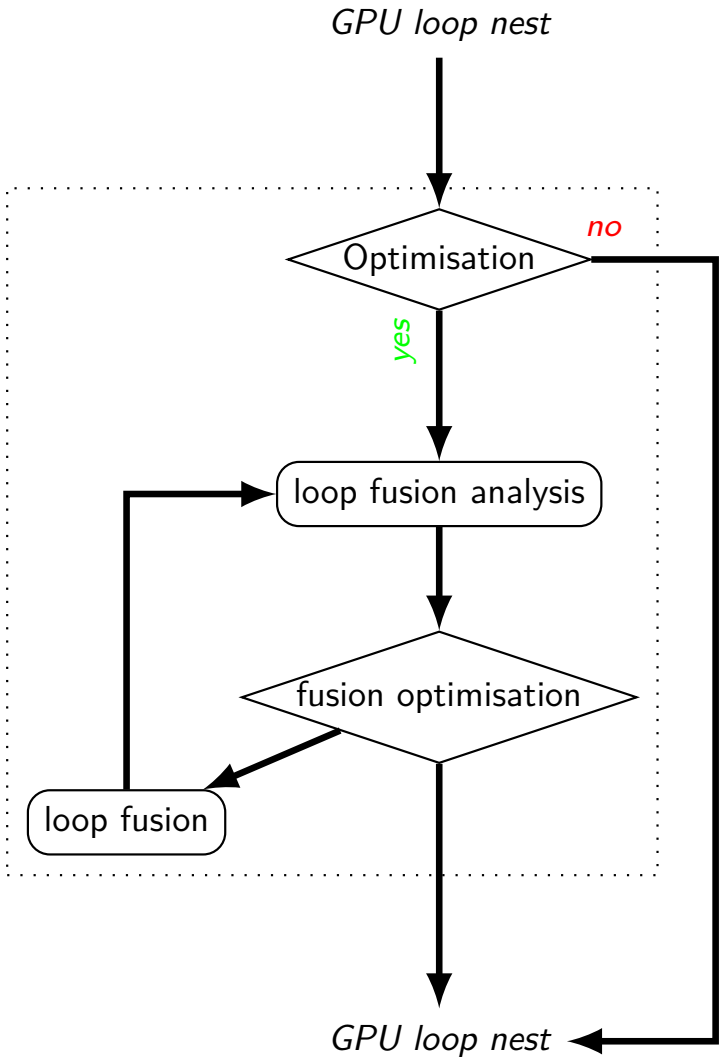
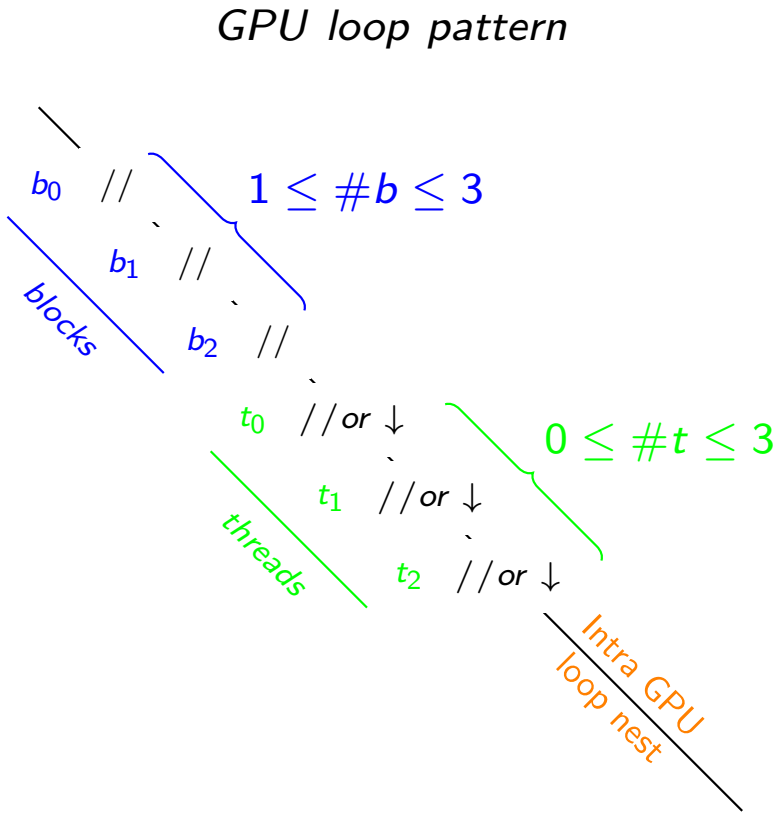
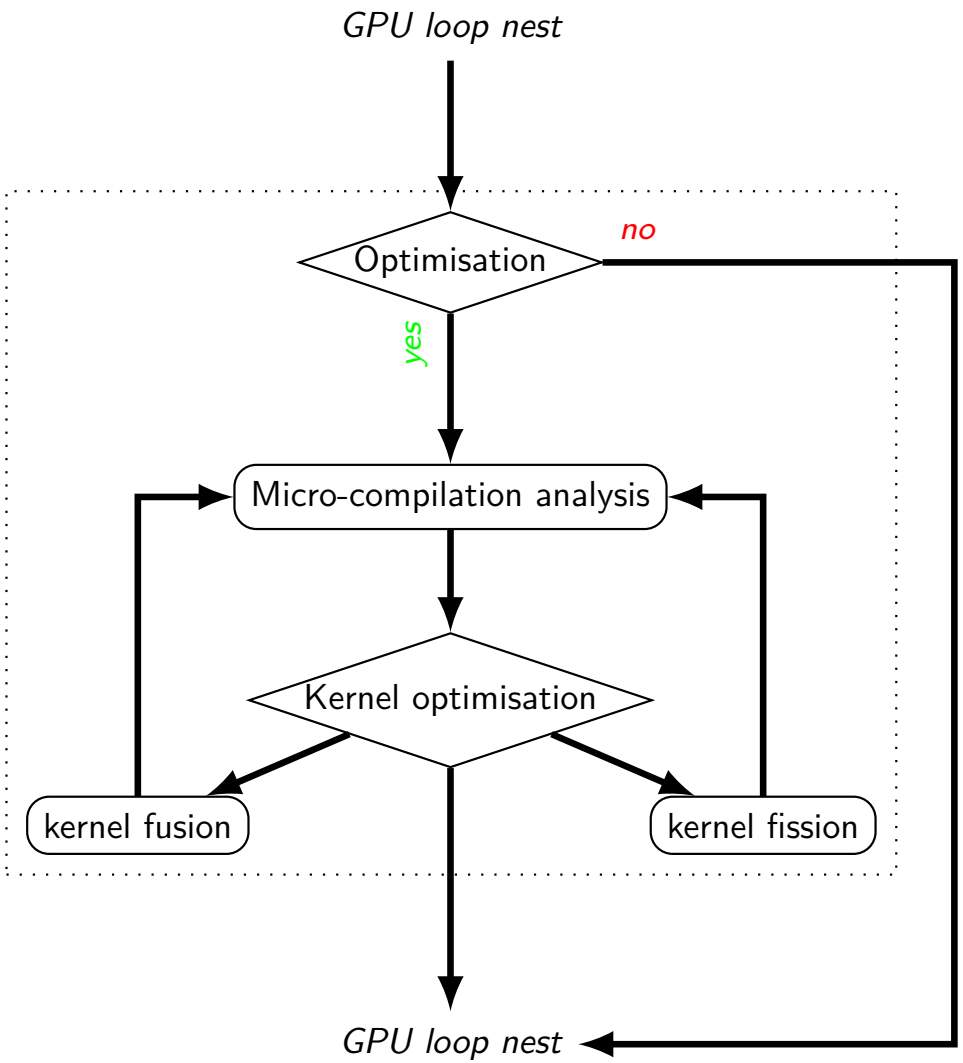
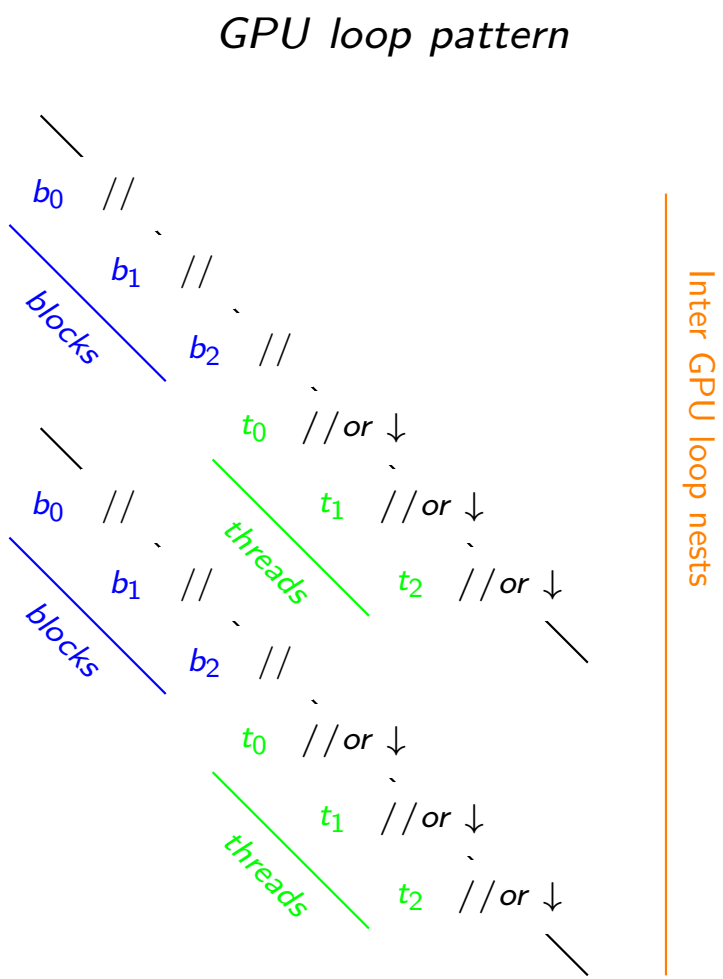
Intra GPU loop nest optimisation





Inter GPU loop nest optimisation





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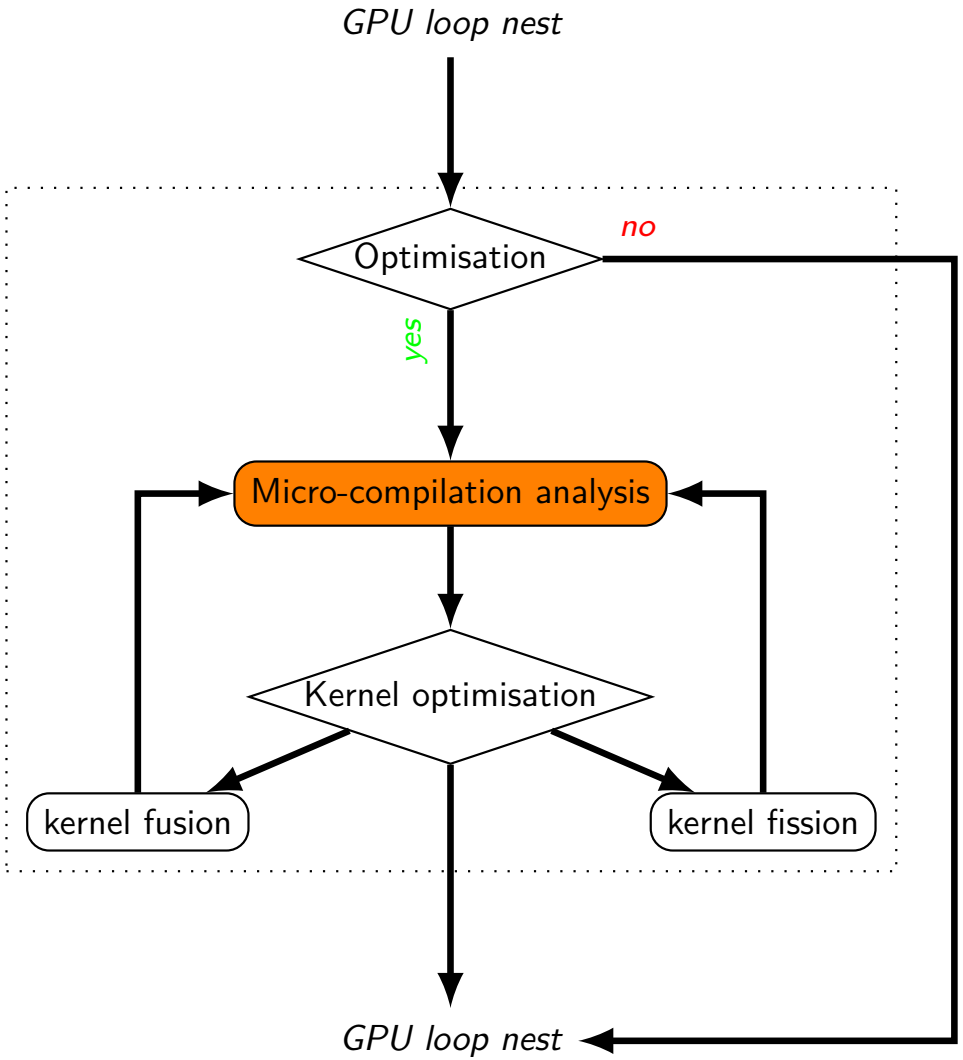

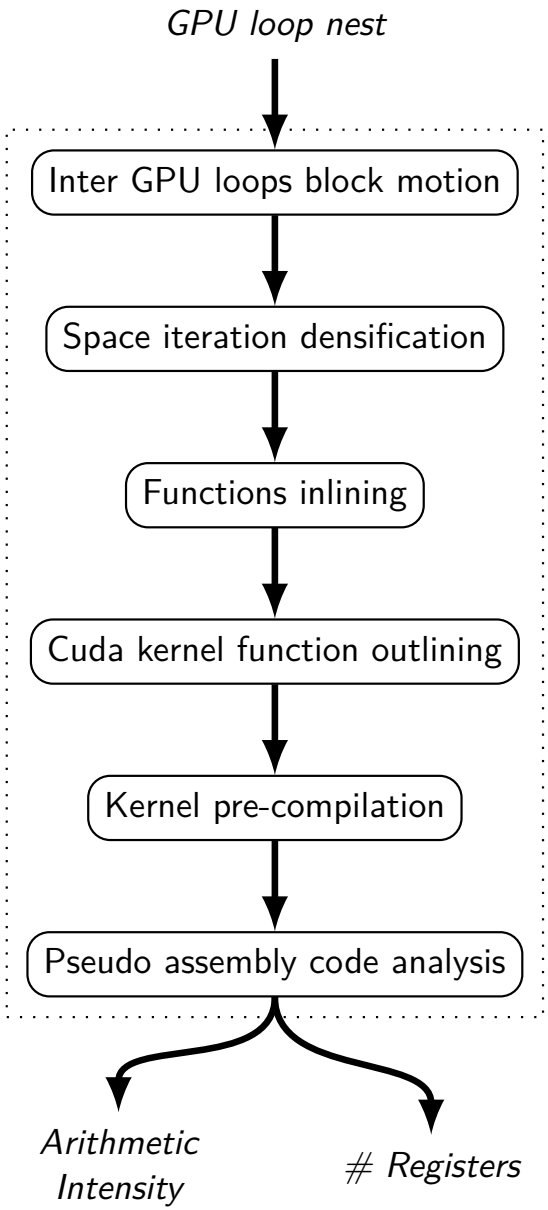

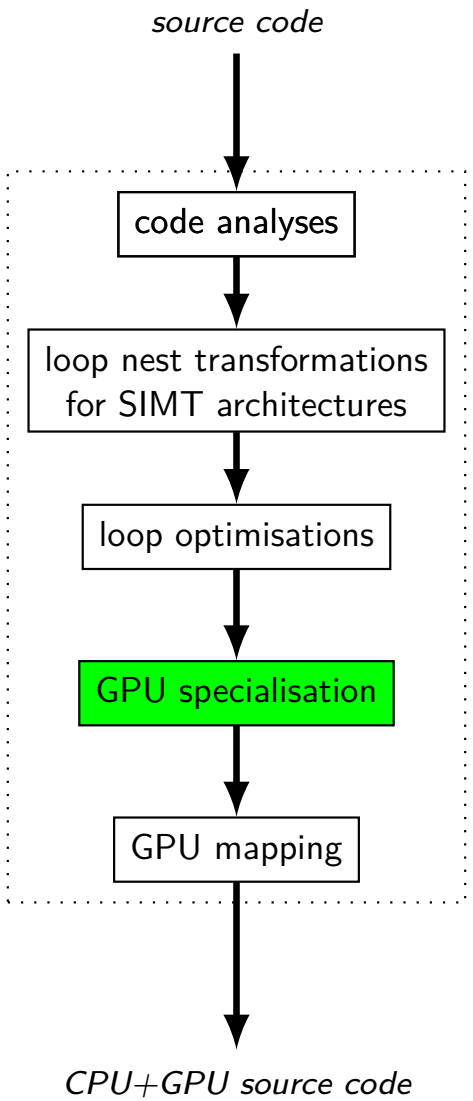
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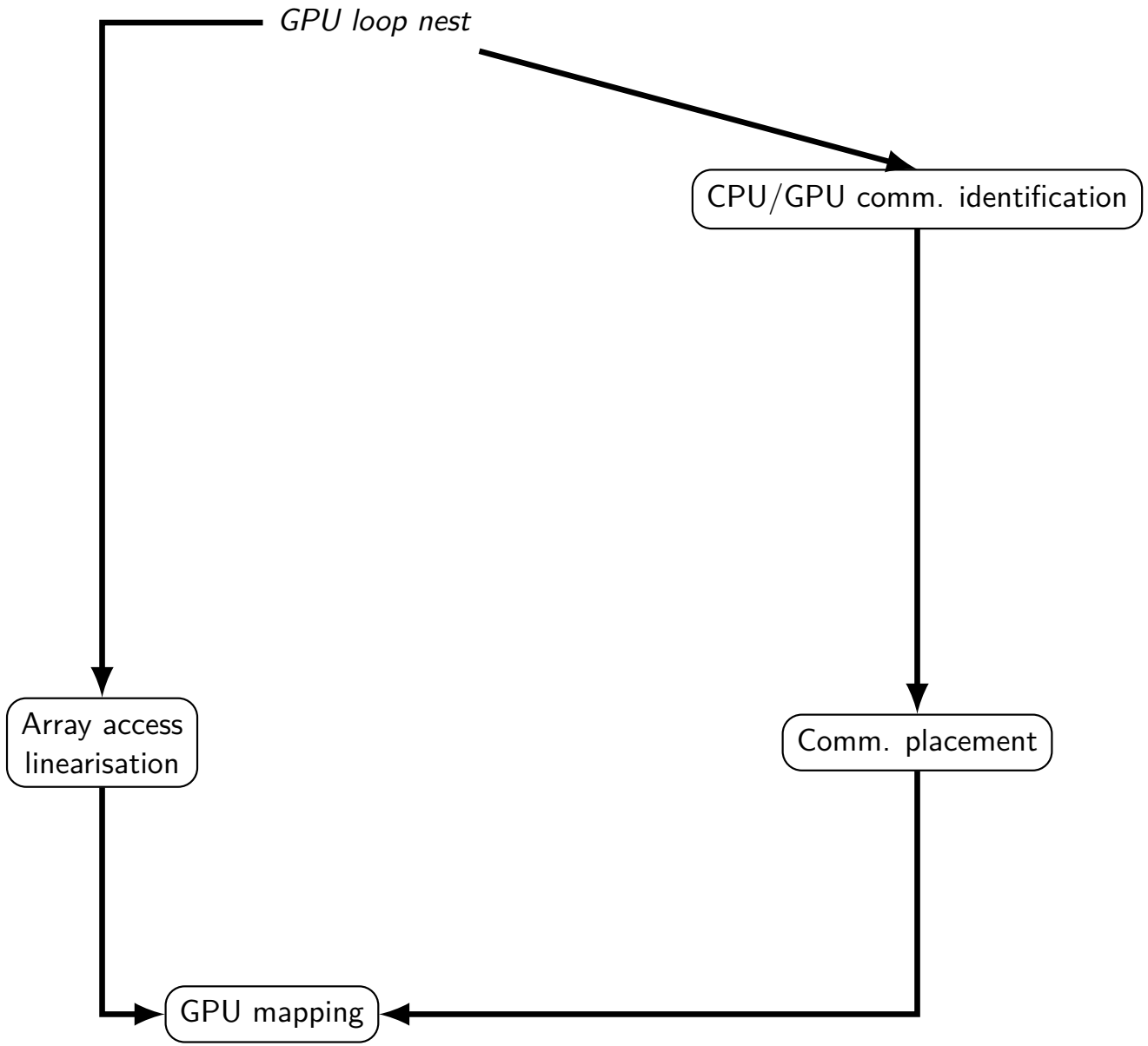
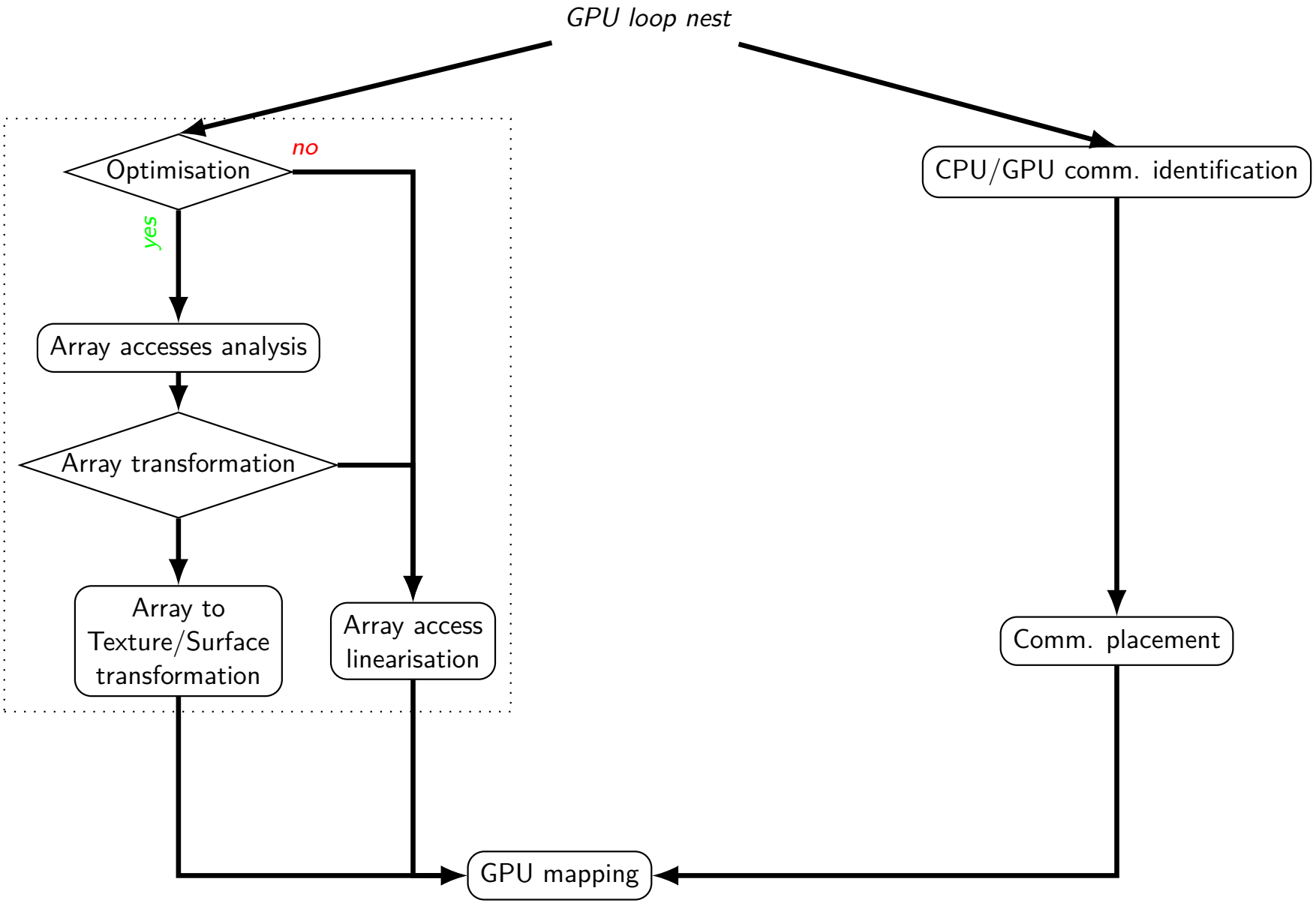
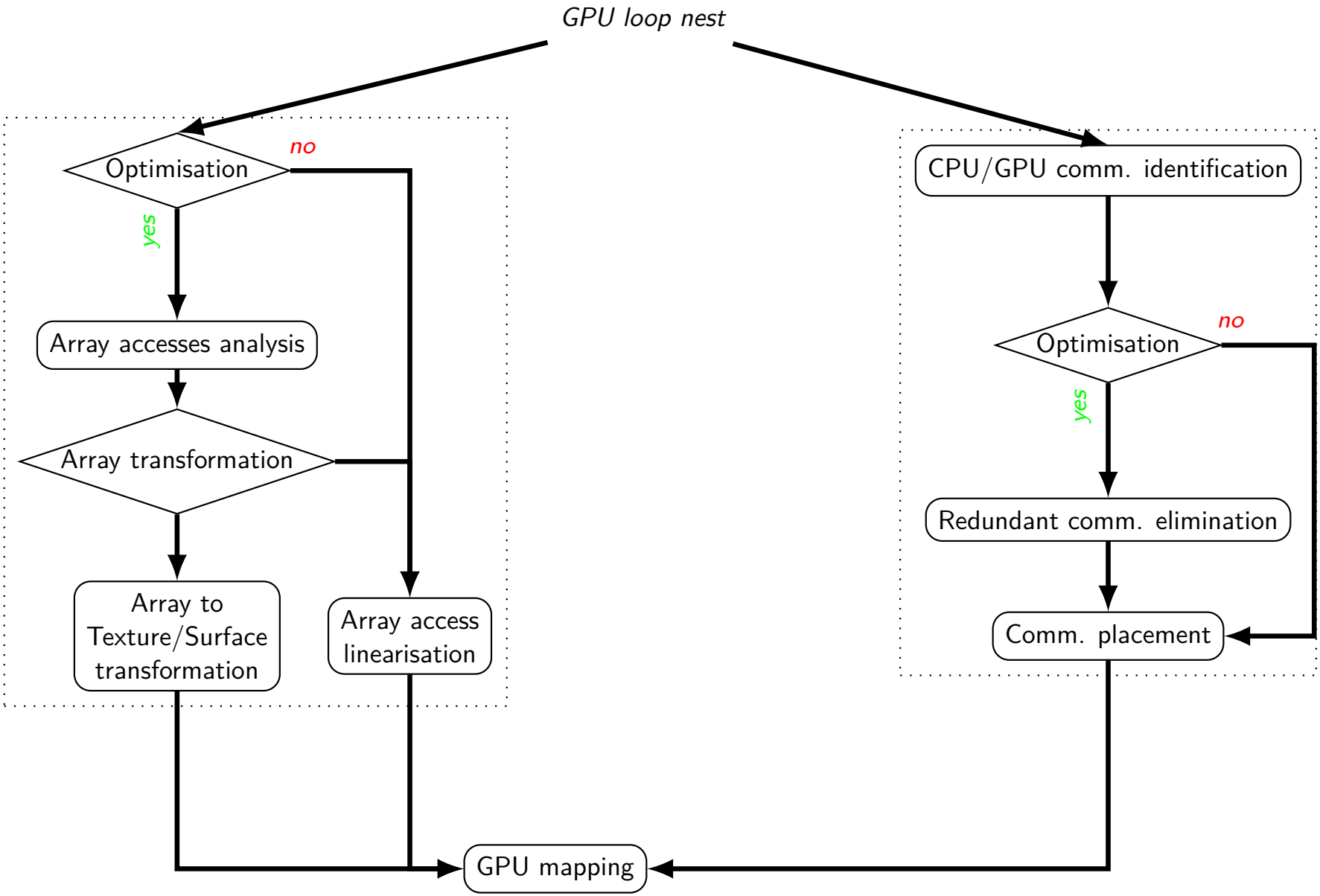
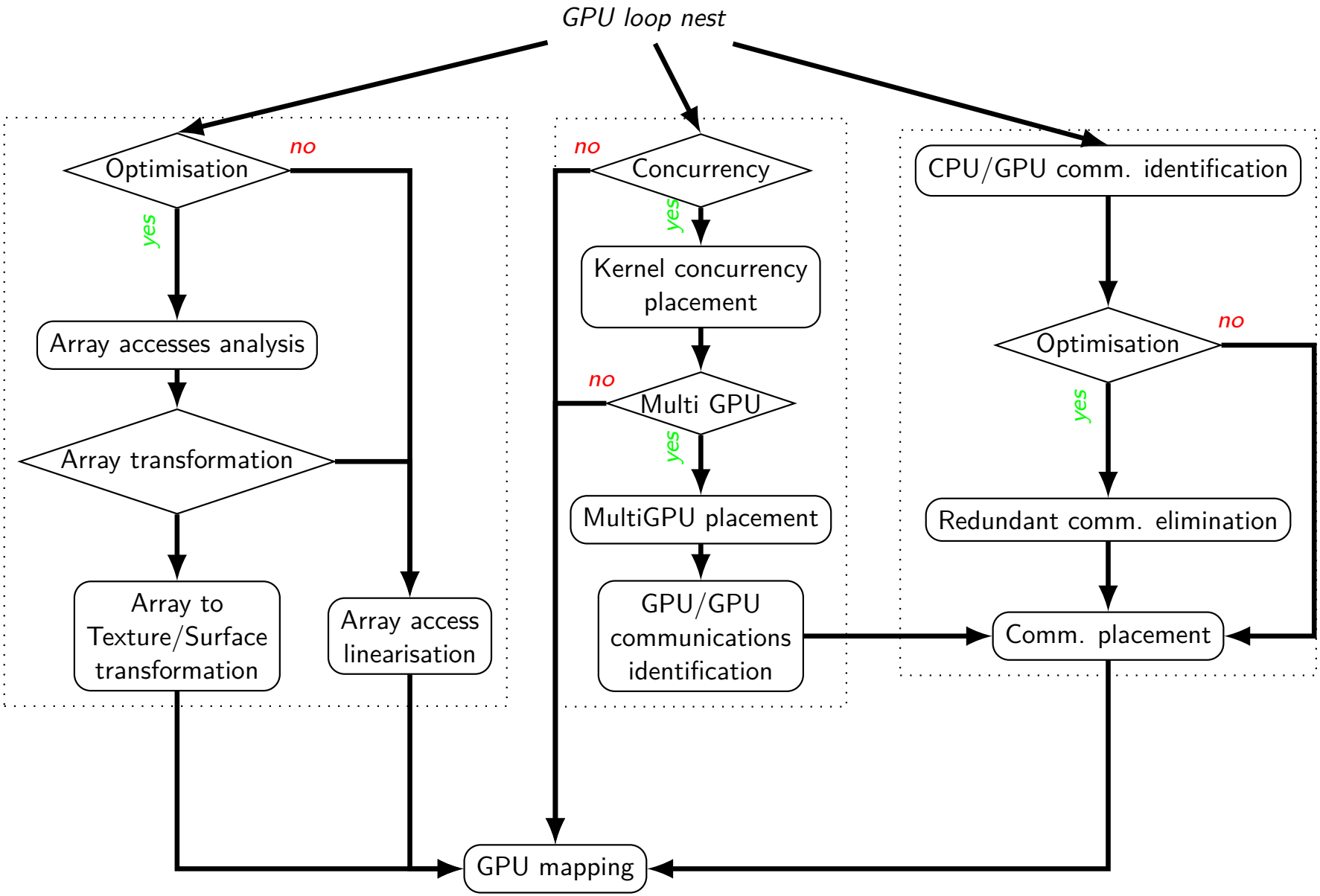

GPU loop nest
CPU/GPU comm. identification
Array access linearisation
Comm. placement
GPU mapping

GPU specialisation



GPU specialisation




GPU loop nest
Optimisation
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Array accesses analysis
Array transformation
Array to Texture/Surface transformation
Array access linearisation
Concurrency
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Kernel concurrency placement
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MultiGPU placement
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CPU/GPU comm. identification
Optimisation
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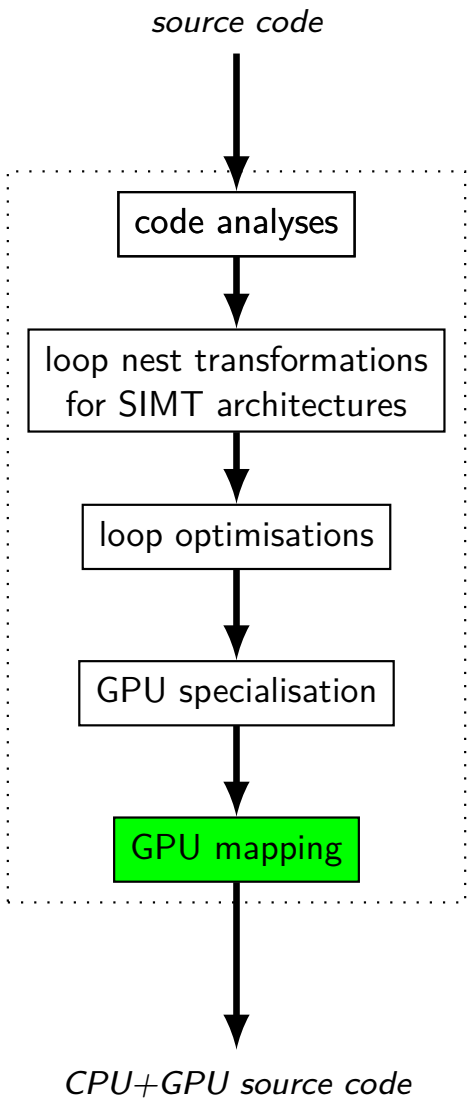
Redundant comm. elimination
Comm. placement
GPU mapping

GPU mapping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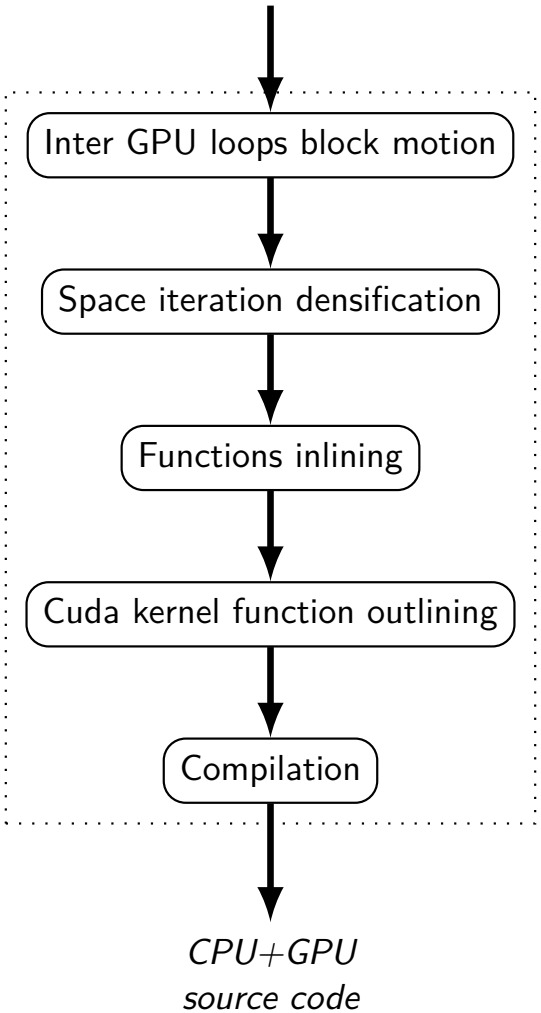
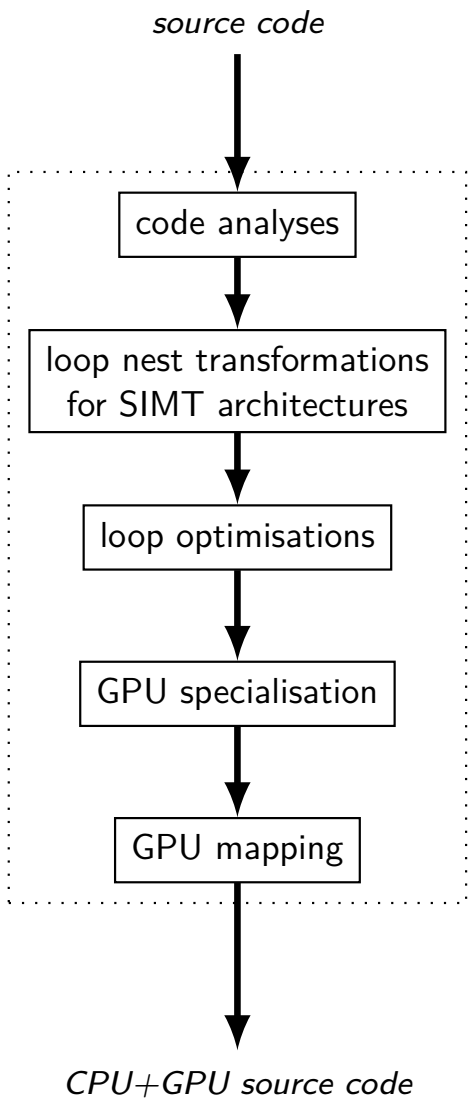

Inter GPU loops block motion
Space iteration densification
Functions inlining
Cuda kernel function outlining
Compilation
CPU+GPU
source code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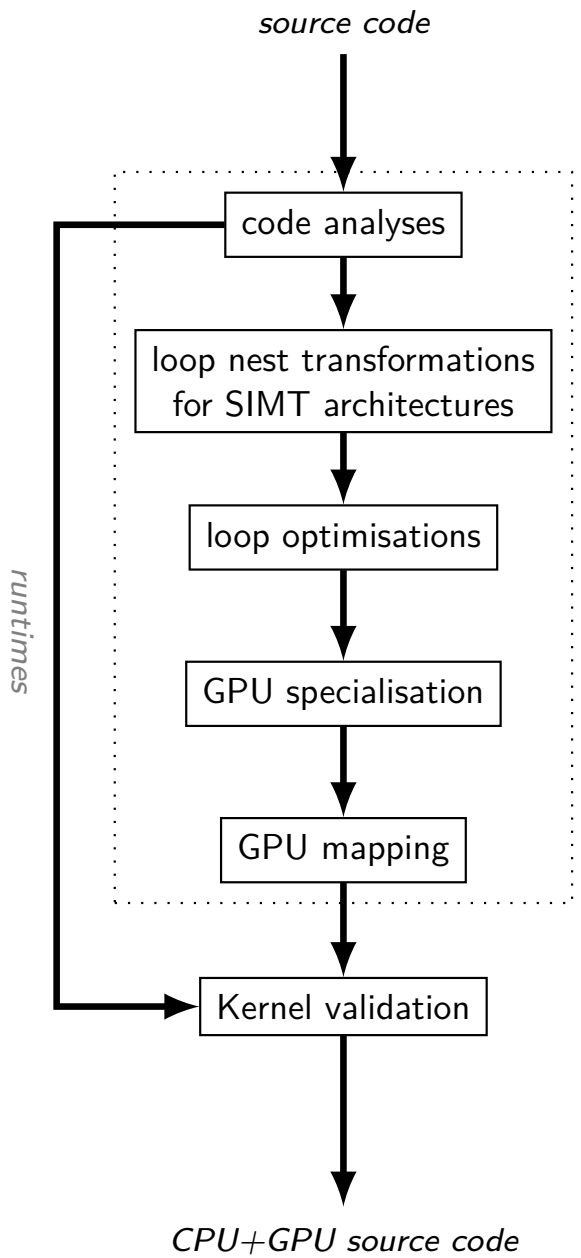
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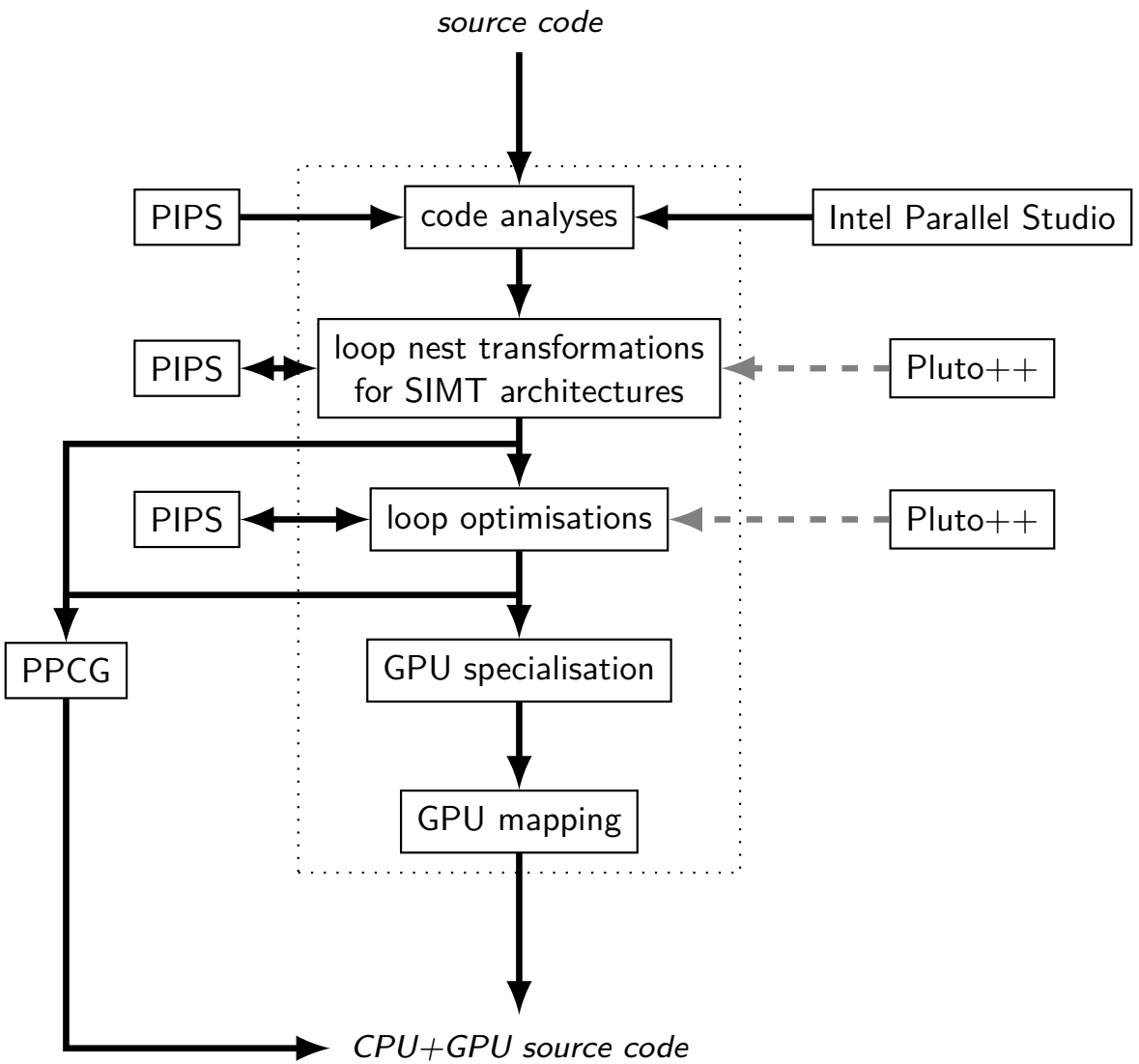
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Pluto++
PIPS
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Pluto++
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GPU mapping
CPU+GPU source code

Validation

Methodology features:

- loop transformations applied:
  - strip mining, fusion, interchange, parallel reduction, tiling
- intra/inter GPU loop nest fusion
- kernel concurrency, multiGPU
- multidimensional array to texture/surface transformation
- CPU/GPU redundant communication elimination
- CPU/GPU asynchonous communications

Validation

Two applications benched:

- Threewise, a local variance computation algorithm
  - Time complexity: $O(N^2) \rightarrow O(N \log N)$
  - Runtime: $[3000ms, 100ms] \rightarrow 27ms$
  - Preserved output results
- SimpleFlow algorithm
  - Global runtime: $50s \rightarrow 6s$
  - Preserved output results

Contributions

- Methodology for GPU
  - with an optional architectural specialisation,
  - not domain specific (image processing),
  - based on arithmetic intensity metric (roofline model),
  - not language/API specific,
  - industrial application oriented.
- Methodology validation:
  - Threewise, a local variance computation algorithm
  - SimpleFlow algorithm
- Criteria developped for methodology driving
- Optimisation of a GPU parallel reduction pattern[2]
- Micro-compilation analysis developped
- Many frameworks have been evaluated:
  - Intel Parallel Studio, PIPS, PPCG, Pluto, ...

[2] Florian Gouin, Corinne Ancourt, and Christophe Guettier. "Threewise: a local variance algorithm for GPU". . In: *19th IEEE International Conference on Computational Science and Engineering (CSE 2016)*. 2016, pp. 257–262.

Perspectives

1. Automatize the methodology
2. Benchmark (validation)
3. Extend to signal processing applications
4. Extend to other GPGPU architectures (AMD)
5. Extend to other parallel architectures (Intel Xeon Phi, Kalray MPPA, ...)