



High-level Techniques for Kernel Fusion and Other Optimizations

The AI technology in Information and Communications Technology domain sharing

Semyon Grigorev

Saint Petersburg State University

December 3, 2025

Problem Statement

- + Library of basic functions is highly optimized
 - But algorithms that utilize it are not

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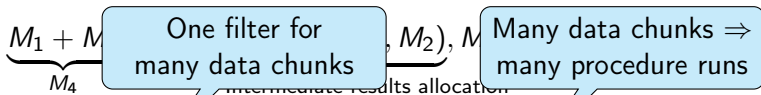
- + Library of basic functions is highly optimized
 - But algorithms that utilize it are not
- Intermediate data structures problem

Highly-optimized
function from linear
algebra library

$$\underbrace{M_1 + M_2}_{M_4} + M_3 \rightsquigarrow \text{add}(\underbrace{\text{add}(M_1, M_2)}_{\text{Intermediate results allocation}}, M_3)$$

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- Parametrization

```
__global__ void handleData (int* filterParams, int* data, ...) {...}
```

Generic function

`filterParams` is static during one data processing session

How can we use this fact to optimize `handleData` procedure?

High-Level Techniques for Code Optimization

- Partial Evaluation¹
- Deforestation²
- Supercompilation³
- Distillation⁴

¹Jones, N.D., Gomard, C.K., Sestoft, P.: Partial Evaluation and Automatic Program Generation.

²Wadler, P.: Deforestation: Transforming Programs to Eliminate Trees.

³Turchin, V.F.: The Concept of a Supercompiler.

⁴Hamilton, G.W.: The Next 700 Program Transformers

High-Level Techniques for Code Optimization

- Partial Evaluation¹
 - Deforestation²
 - Supercompilation³
 - Distillation⁴
- ✓ Can be used to solve problems described above
- ? Well-suited for functional-first programming languages
- ☹ Not for Python or C

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High-Level Languages For High-Performance Computing (HLL for HPC)

- Functional, functional-first programming languages for
 - ▶ GPGPU programming
 - ▶ FPGA programming (program specific processors)
 - ▶ Hardware synthesis

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- Expressivity, high-level composable primitives
- Type safety, static code checks
- Specific optimizations
 - ▶ Fusion (stream fusion)
 - ▶ Partial evaluation
 - ▶ Deforestation

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 - ▶ Fusion (stream fusion)
 - ▶ Partial evaluation
 - ▶ Deforestation
- Specific hardware

- **AnyDSL**: A partial evaluation framework for programming high-performance libraries
 - ▶ Saarland University, German Research Center for Artificial Intelligence (DFKI)
- **Futhark**: high-performance purely functional data-parallel array programming
 - ▶ University of Copenhagen
- **LIFT**: high-level functional data parallel language for portable HPC
 - ▶ University of Edinburgh, University of Glasgow
 - ▶ Supported by HIRP FLAGSHIP
- **Haflang**: special purpose processor for accelerating functional programming languages
 - ▶ Heriot Watt University
 - ▶ Supported by Xilinx and QBayLogic
- ...

- ✓ Stream Fusion — for linear data
- ✓ XLA — for dense data
- ⚙ MLIR⁵
 - ? For general sparse computations
 - ▶ Sparse attention
 - ▶ Graph neural networks
 - ▶ For GPGPU and other accelerators

⁵E.g. mlir-graphblas

Distillation for Sparse Linear Algebra Kernels (Work in Progress)

- Distillation⁶
 - ▶ High-level program transformation technique
 - ▶ Includes kernel-fusion-like optimization

⁶<https://github.com/YaccConstructor/Distiller>

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⁸<https://github.com/sedwards-lab/fhw>

Distillation for Sparse Linear Algebra Kernels (Work in Progress)

- Distillation⁶
 - ▶ High-level program transformation technique
 - ▶ Includes kernel-fusion-like optimization
- Special hardware
 - ▶ Reduceron⁷
 - ★ Lambda-processor
 - ★ Migration to Haflang
 - ▶ FHW⁸
 - ★ Functional program to hardware translator
 - ★ Program-specific accelerator

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Preliminary Evaluation: Input

- A set of functions for sparse matrices manipulation
 - ▶ `addMask m1 m2 m3 = mask (mtxAdd m1 m2) m3`
 - ▶ `kronMask m1 m2 m3 = mask (kron m1 m2) m3`
 - ▶ `addMap m1 m2 = map f (mtxAdd m1 m2)`
 - ▶ `kronMap m1 m2 = map f (kron m1 m2)`
 - ▶ `seqAdd m1 m2 m3 m4 = mtxAdd (mtxAdd (mtxAdd m1 m2) m3) m4`
- All matrices are in quad-tree format

Preliminary Evaluation: Results (In Hardware Emulator)

Function	Matrix size				Interpreter		Reduceron	FHW
	m1	m2	m3	m4	Steps	Reads	Ticks	Ticks
seqAdd	64×64	64×64	64×64	64×64	2.7	1.9	1.8	1.4
addMask	64×64	64×64	64×64	—	2.1	1.8	1.4	1.4
kronMask	64×64	2×2	128×128	—	2.2	1.9	1.4	2.7
addMap	64×64	64×64	—	—	2.5	1.7	1.7	1.5
kronMap	64×64	2×2	—	—	2.9	2.2	1.8	2.0

Table: Evaluation results: original program to distilled one ratio of measured metrics

- Convolution (1D, 2D, 3D) \Rightarrow Data (e.g. image) processing, including AI
- Substring matching \Rightarrow Data curving (cyber forensics)

Partial Evaluation or Specialization

$$\underbrace{\llbracket \text{handleData} \rrbracket}_{\text{handleData}}[\text{filterParams}, \text{data}] = \underbrace{\overbrace{\llbracket \text{mix} \rrbracket}_{\text{partial evaluator}}[\llbracket \text{handleData}, \text{filterParams} \rrbracket]}_{\text{handleData}_{\text{mix}}}[\text{data}]$$

$$\underline{\llbracket \text{mix} \rrbracket[\llbracket \text{handleData}, [2; 3] \rrbracket]}$$

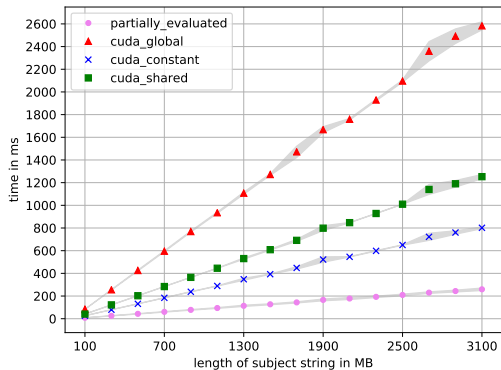
```
handleData (filterParams, data)
{
  res = new List()
  for d in data
    for e in filterParams
      if d % e == 0
        then res.Add(d)
  return res
}
```

```
handleData_mix (data)
{
  res = new List()
  for d in data
    if d % 2 == 0 ||
      d % 3 == 0
      then res.Add(d)
  return res
}
```

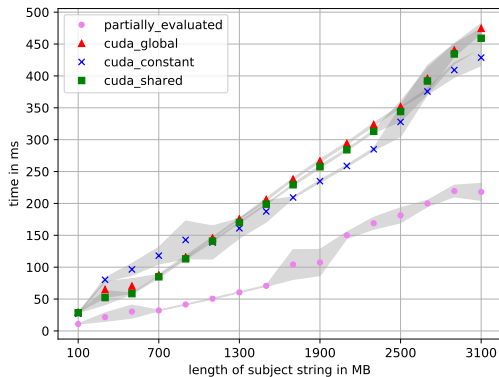
- We use **AnyDSL** framework for specialization
 - ▶ Special DSL which can be specialized and compiled
 - ▶ Ahead-of-time specialization
- Algorithms
 - ▶ Naïve multiple substring matching
 - ▶ 2D convolution
- Hardware
 - ▶ **GTX-1070**: Pascal architecture, 8GB GDDR5, 1920 CUDA cores
 - ▶ **Tesla T4**: Turing architecture, 16GB GDDR6, 2560 CUDA cores

Evaluation: Substring Matching

- Application: data curving
- Subject string: byte sequence from real hard drive
- Patterns: 16 file signatures from GCK's file signatures table⁹



Results for GTX-1070

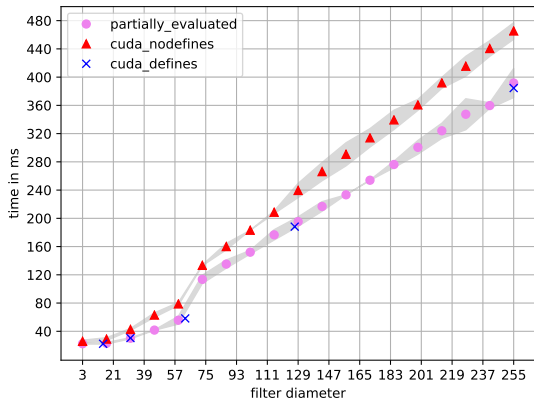


Results for Tesla T4

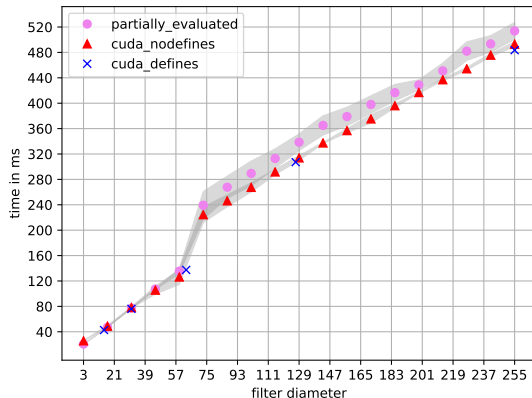
⁹https://www.garykessler.net/library/file_sigs.html

Evaluation: 2D Convolution

- Application: image processing
- Subject image: random image of size 1GB
- Filters: random square filters with diameter 3 to 255



Results for GTX-1070



Results for Tesla T4

Conclusion

- Distillation can (partially) solve kernel fusion problem
- Partial evaluation can !!!
- Functional-first programming languages !!!

- Associate professor at St. Petersburg State University
- Head of research group
- Research area
 - ▶ **High-performance generic linear algebra**
 - ★ **Advanced optimization techniques** including software-hardware co-design
 - ★ **GPGPU-powered** sparse linear algebra libraries
 - ▶ High-performance graph analysis



- Email: s.v.grigoriev@mail.spbu.ru
- GitHub: [gsvgit](#)
- Google Scholar: [Semyon Grigorev](#)
- DBLP: [Semyon V. Grigorev](#)