GPU Taint Tracking

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July 12, 2017

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Vulnerability of GPUs

Sensitive Data on the GPU

- Many GPU applications use sensitive data:
  - Machine learning, data encryption, computer vision.

Face Recognition Input

Sensitive Data on the GPU

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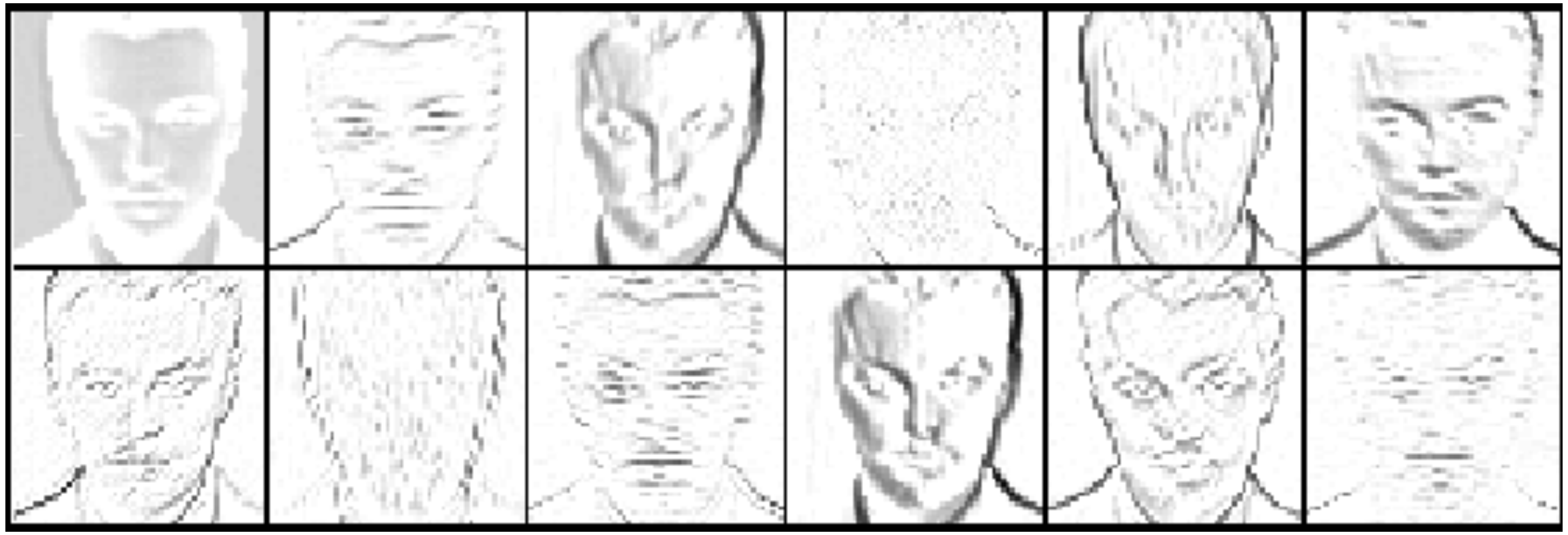
  - Machine learning, data encryption, computer vision.

Face Recognition
Input



Face Recognition
Leaked Features

Memory Protection

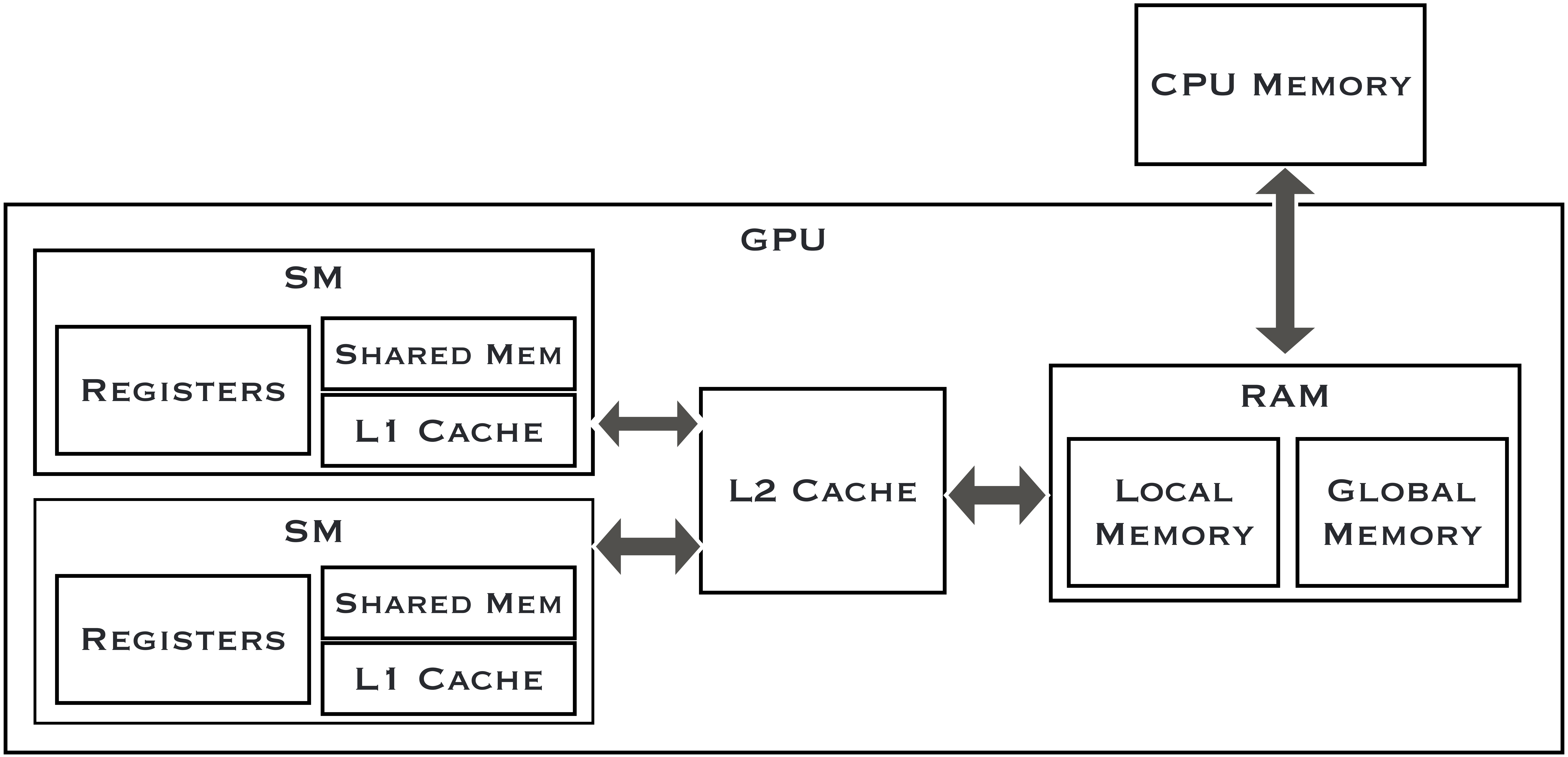
- Virtual Memory
  - Address Space Layout Randomization
  - Process Isolation
  - Page Protection
- Bounds Checking
- Memory Erasure

None of these are **fully** available on the GPU!

Memory Protection

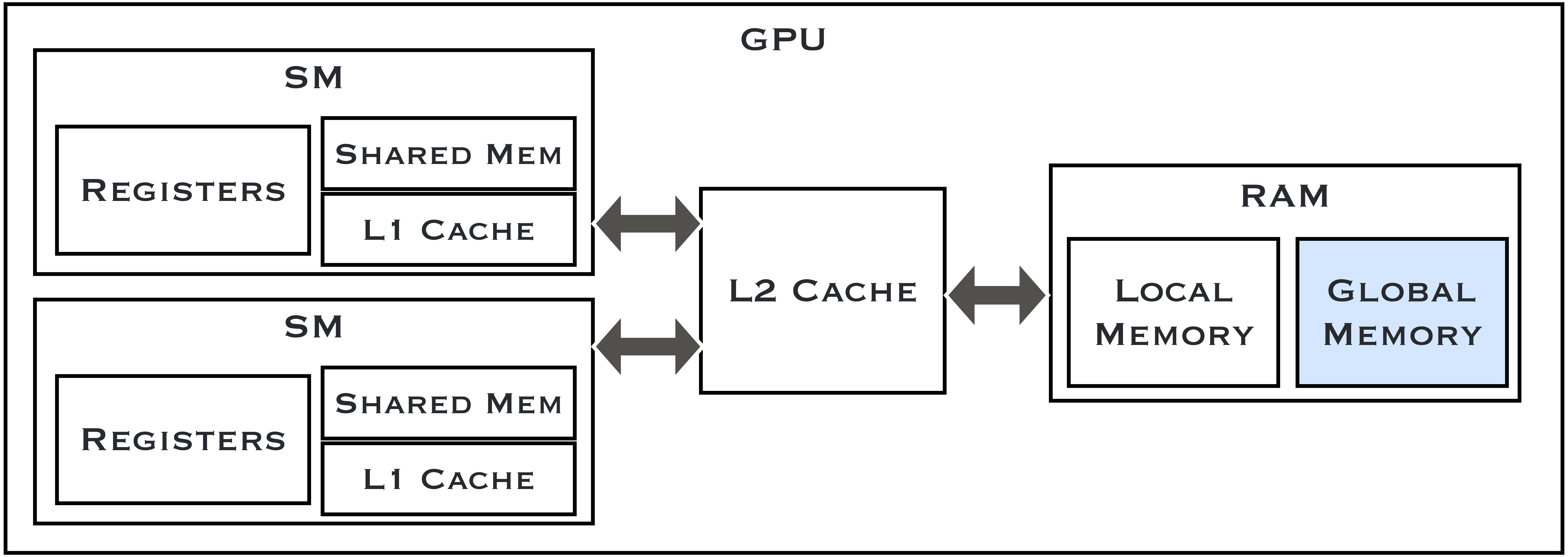
- Without address space layout randomization, an attacker can predict where GPU data is stored. [Patterson, ISU thesis 2013]
- Without process isolation, an attacker can peek into another GPU process, steal encryption keys. [Pietro+, TECS 2016]
- Without page protection and bounds checking, an attacker can force a GPU program to write to non-permissive memory regions. [Vasiliadis+, CCS 2014]
- Without a reliable way to control or erase GPU thread-private memories, a user cannot keep their data contained. [Pietro+, TECS 2016]

GPU Memory


CPU Memory
GPU
SM
Registers
Shared Mem
L1 Cache
SM
Registers
Shared Mem
L1 Cache
L2 Cache
RAM
Local Memory
Global Memory

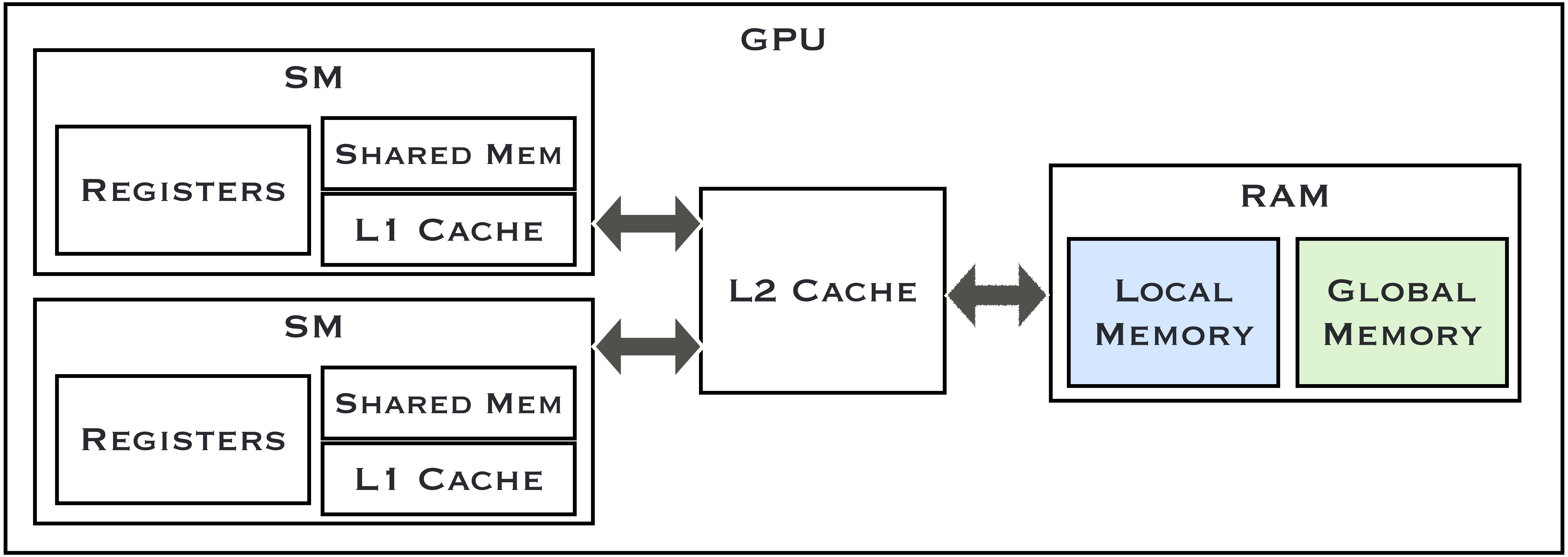
Global memory

- Easily accessible to an attacker.



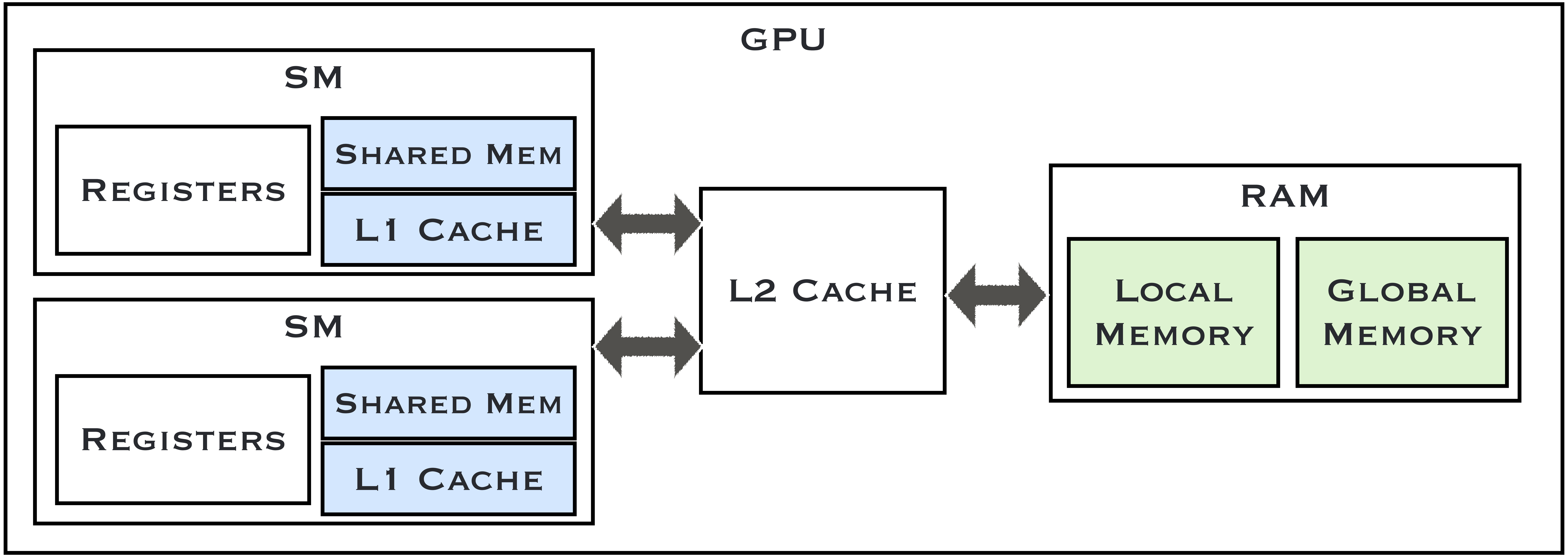
Local Memory

- Used for spilled registers; inaccessible to programmer
- Accessible by attacker through global memory



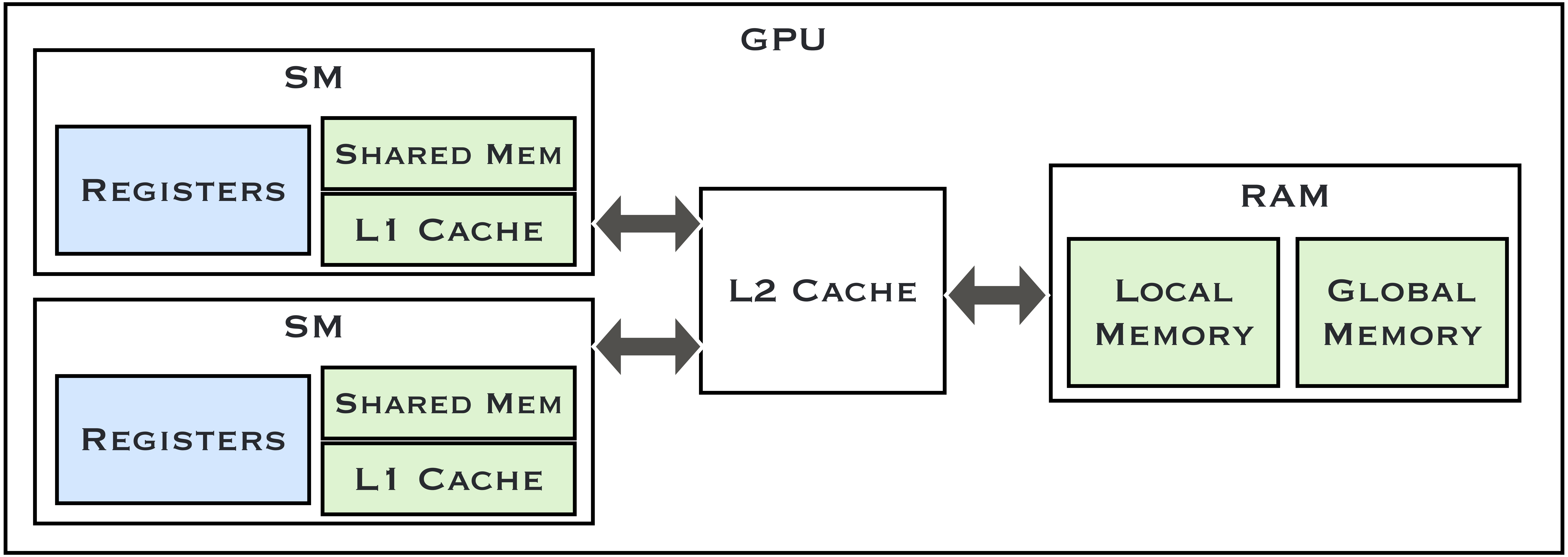
Shared Memory & L1 Cache

- Shared mem is accessible to attacker after function ends
- On some GPUs, L1 cache can leak into shared memory



Register File

- Designed to be inaccessible to programmer.
- Accessible to attackers after GPU function finishes.



Dynamic Taint Analysis

- Common technique for monitoring sensitive data
- Marks (taints) sensitive data and tracks taint at runtime
- Has extensive CPU work with various implementations:
  - Compile-time instrumentation [Lin+, ICC 2010]
  - Dynamic instrumentation [Kemerlis+, VEE 2012]
  - Emulation [Bosman+, RAID 2011]
  - Virtual machine [Enck+, TOCS 2014]
- Not previously attempted for GPU programs

Challenges of GPU Taint Tracking

- Must track several memory types
- Dynamic instrumentation infeasible
    - Lack of support from OS or driver;
    - Cannot intercept/modify instructions on the fly.
- Emulation is unappealing
    - Up to 1000x slowdown [Farooqui+, GPGPU 2011]
- Virtual machines are unhelpful
    - Cannot monitor data in GPU

Our Contributions

- First GPU dynamic taint tracking system.
    - Compile-time binary instrumentation
    - Dynamic tracking
    - GPU-specific optimizations to minimize overhead.
    - Filter out unnecessary tracking instructions
    - Improves tracking performance by 5 to 20 times

2 Taint Tracking

Taint Tracking

- Maintains taint map; **one taint bit** for each memory location.
- Monitors instructions & operands, propagating taint values.

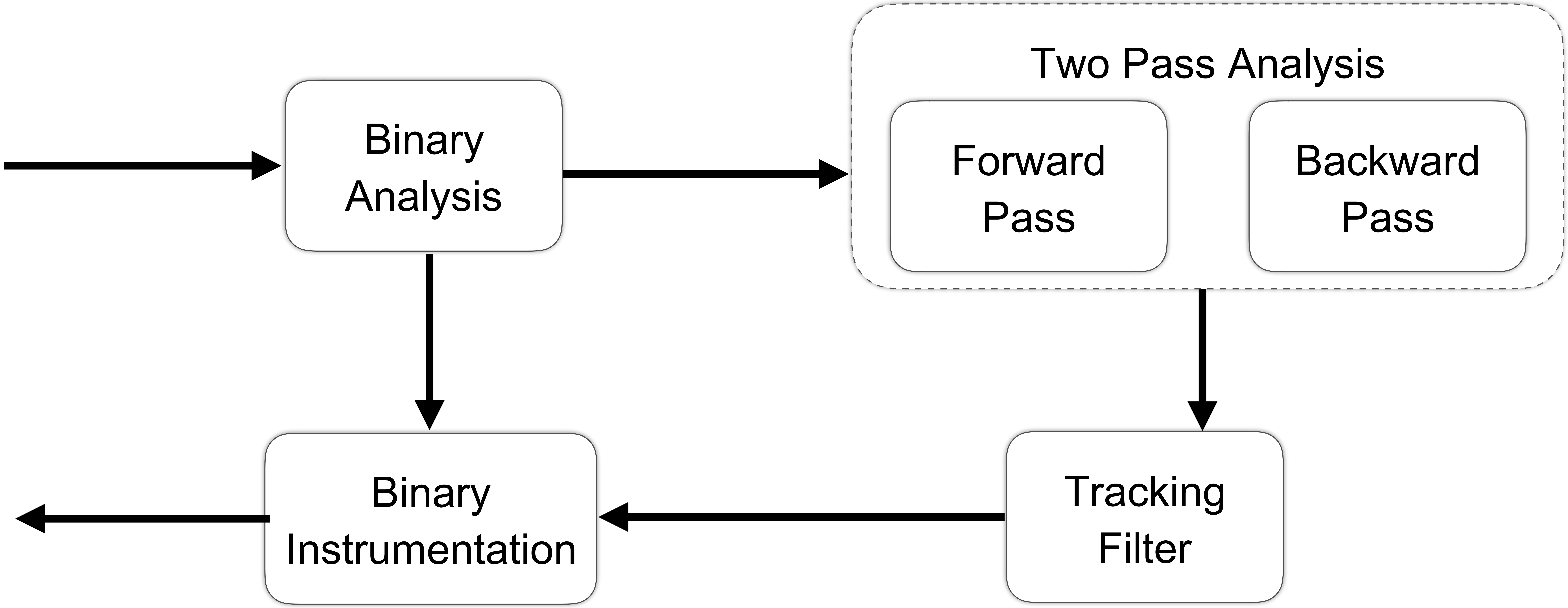
```
void foo() {
   b = a;
   d = b + c;
}
```

Original code

```
void foo_taint_tracking() {
   taint(b) = taint(a);
   taint(d) = taint(b) || taint(c);
}
```

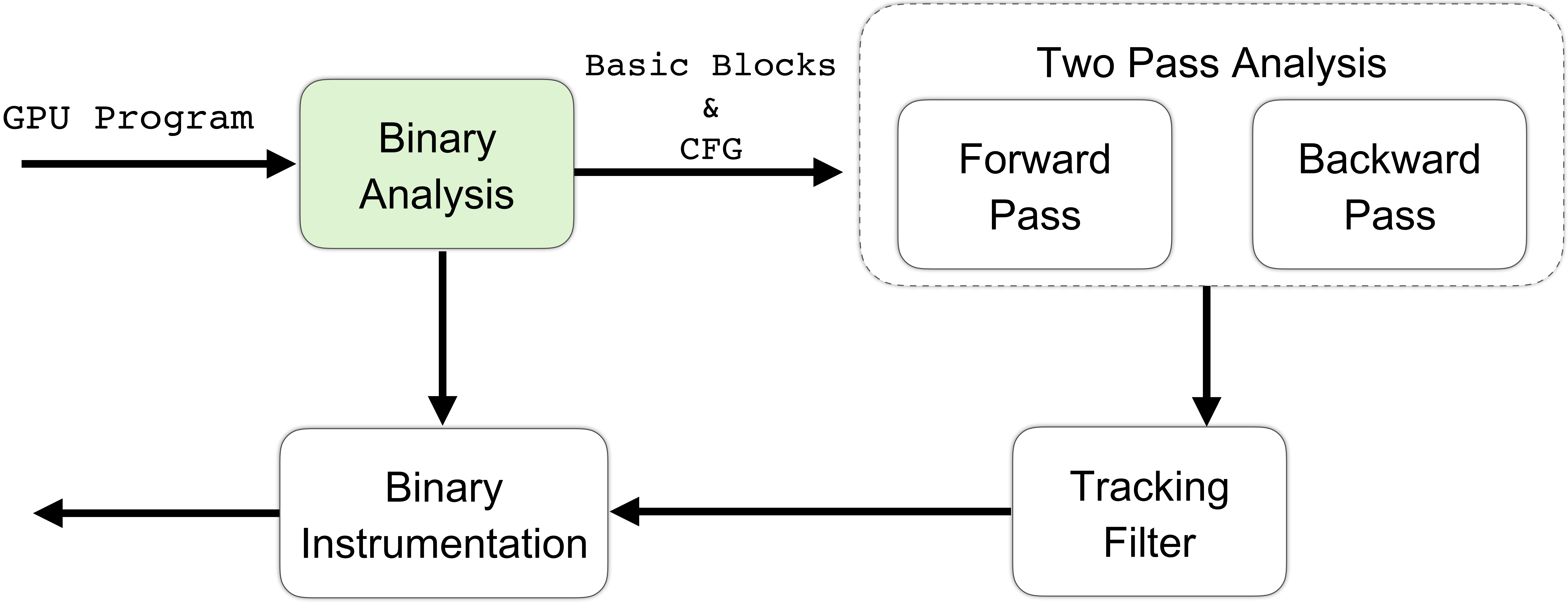
Taintedness propogation

Our Taint Tracking System



3 Analysis

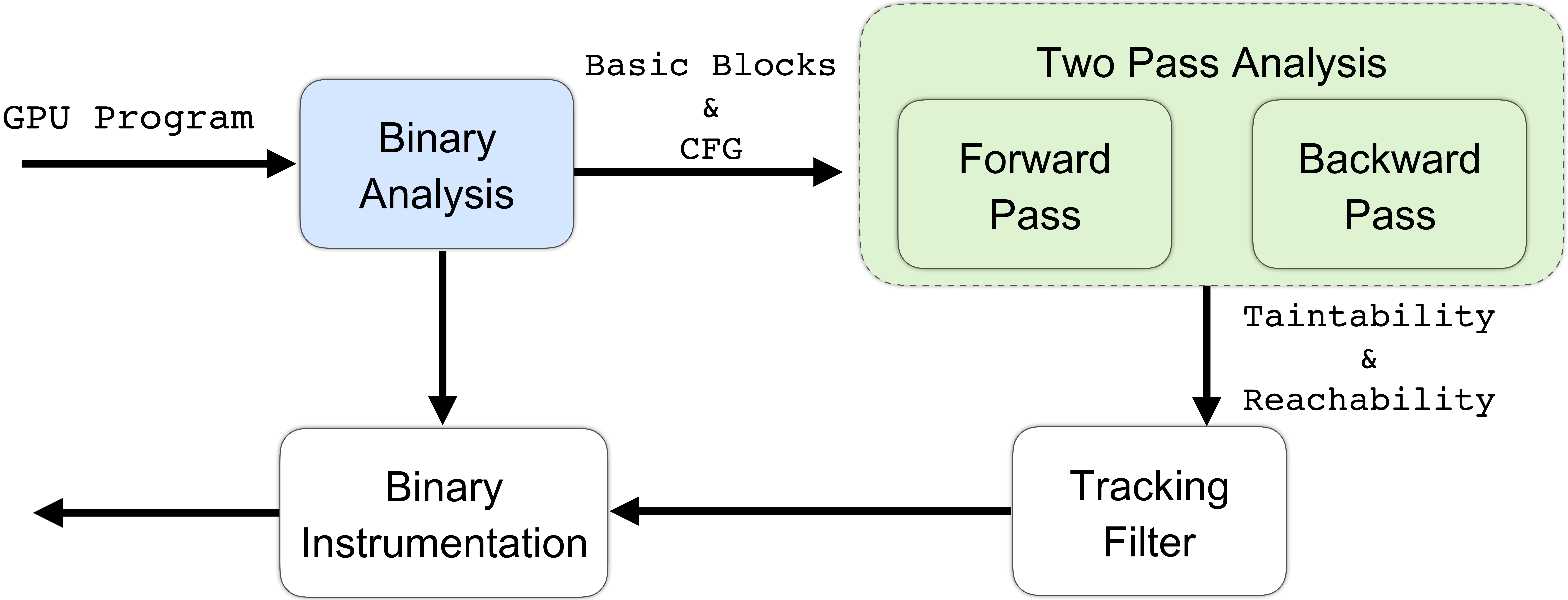
Our Taint Tracking System



GPU Behavior

- We observe that not everything needs to be tracked.
- Some GPU data is untaintable or cannot spread taint.
    - Thread ID
    - Grid Size
    - Constant memory
    - Loop Iterators
    - Immediate values
- These operands and instructions can be identified by analyzing the basic blocks and control flow graph.

Our Taint Tracking System



Two Pass Analysis

- Backward pass
  - Identifies & marks taint sinks
  - Propagates markings backward
- Forward pass
  - Identify & marks potential taint sources
  - Propagates markings forward
- Two-pass analysis
  - Combine markings from both passes

Backward Pass

Block4:

R0 = R1 + R2;	reachable = {R1, R2, R3}
R1 = **R1** + **R3**;	reachable = {R1, R2, R3}
R0 = [R1];	reachable = {R1, R2, R3}
R2 = **R3** * **R2**;	reachable = {R1, R2, R3}
[R1] = **R2**;	reachable = {R1, R2, R3}
R0 = **R1** * **R3**;	reachable = {R1, R3}
BRA block5; →	reachable = {**R0, R3**}

Backward Pass

```
Block4:
  R0 = R1 + R2;        reachable = {R1, R2, R3}
  R1 = R1 + R3;        reachable = {R1, R2, R3}
  R0 = [R1];           reachable = {R1, R2, R3}
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  BRA block5;    ---->   reachable = {R0, R3}
```

Backward Pass

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  R0 = R1 * R3;        reachable = {R1, R3}
  BRA block5;   --->   reachable = {R0, R3}
```

Forward Pass

Block4:	taintable = {**R1**}
R0 = **R1** + R2;	taintable = {R0, R1}
R1 = **R1** + R3;	taintable = {R0, R1}
R0 = **[R1]**;	taintable = {R0, R1}
R2 = R3 * R2;	taintable = {R0, R1}
[R1] = R2;	taintable = {R0, R1}
R0 = **R1** * R3;	taintable = {R0, R1}
BRA block5;	

Forward Pass

Block4:	taintable = {R1}
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Forward Pass

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R0 = **R1** * R3;	taintable = {R0, R1}
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Forward Pass

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Block4:
    R0 = R1 + R2;
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    [R1] = R2;
    R0 = R1 * R3;
    BRA block5;
```

taintable = {R1}
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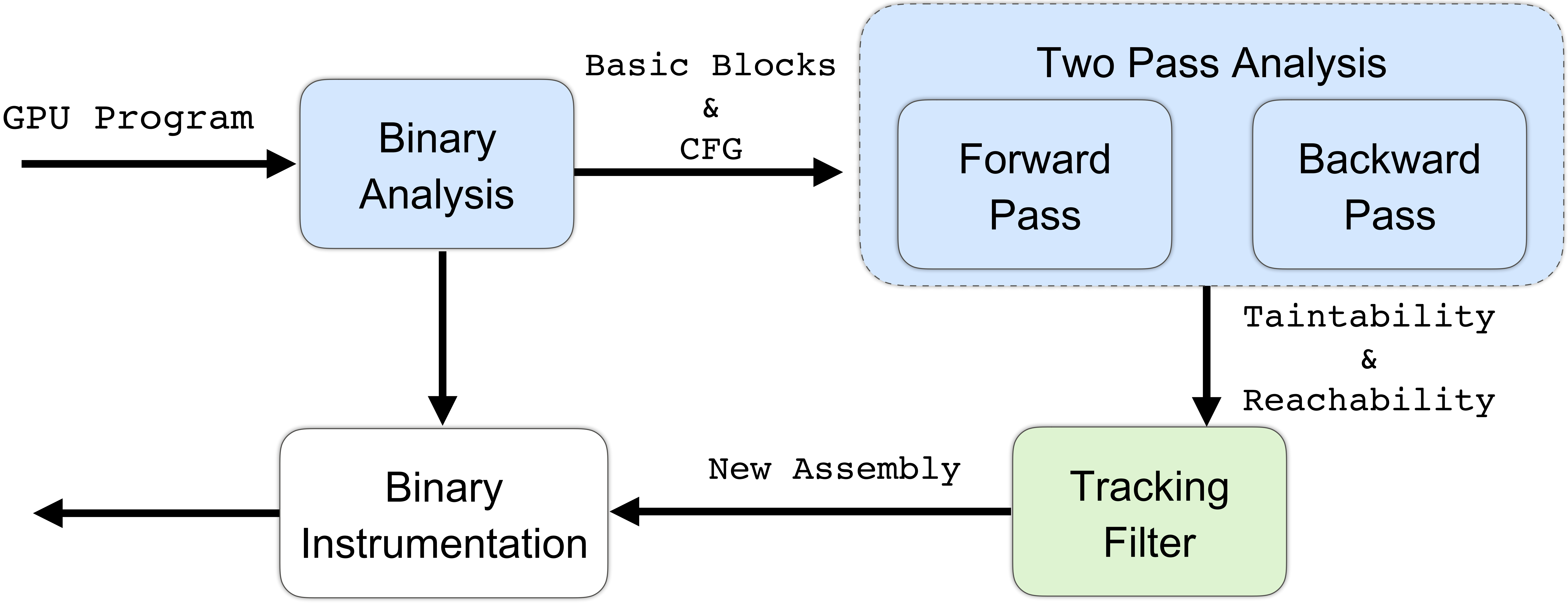
4 Instrumentation

Our Taint Tracking System



Naive Tracking Code

Block4:

$R_0 = R_1 + R_2;$

$R_1 = R_1 + R_3;$

$R_0 = [R_1];$

$R_2 = R_3 * R_2;$

$[R_1] = R_2;$

$R_0 = R_1 * R_3;$

BRA block5;

Naive Tracking Code

Block4:

```
R0 = R1 + R2;
    t(R0) = t(R1) | t(R2)
R1 = R1 + R3;
    t(R1) = t(R1) | t(R3)
R0 = [R1];
    t(R0) = t([R1])
R2 = R3 * R2;
    t(R2) = t(R3) | t(R2)
[R1] = R2;
    t([R1]) = t(R1) | t(R2)
R0 = R1 * R3;
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BRA block5;
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   t(R2) = t(R3) | t(R2)
[R1] = R2;
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[R1] = R2;
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[R1] = R2;
    t([R1]) = t(R1) | t(R2)
R0 = R1 * R3;
    t(R0) = t(R1) | t(R3)
BRA block5;
```

Filtered Tracking Code

```
Block4:
    R0 = R1 + R2;
      t(R0) = t(R1) | t(R2)
    R1 = R1 + R3;
      t(R1) = t(R1) | t(R3)
    R0 = [R1];
      t(R0) = t([R1])
    R2 = R3 * R2;
      t(R2) = t(R3) | t(R2)
    [R1] = R2;
      t([R1]) = t(R1) | t(R2)
    R0 = R1 * R3;
      t(R0) = t(R1) | t(R3)
    BRA block5;
```

Filtered Tracking Code

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R0 = [R1];
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R2 = R3 * R2;
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BRA block5;
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Filtered Tracking Code

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R0 = [R1];

R2 = R3 * R2;

[R1] = R2;
  t([R1]) = t(R1)
R0 = R1 * R3;
  t(R0) = t(R1)
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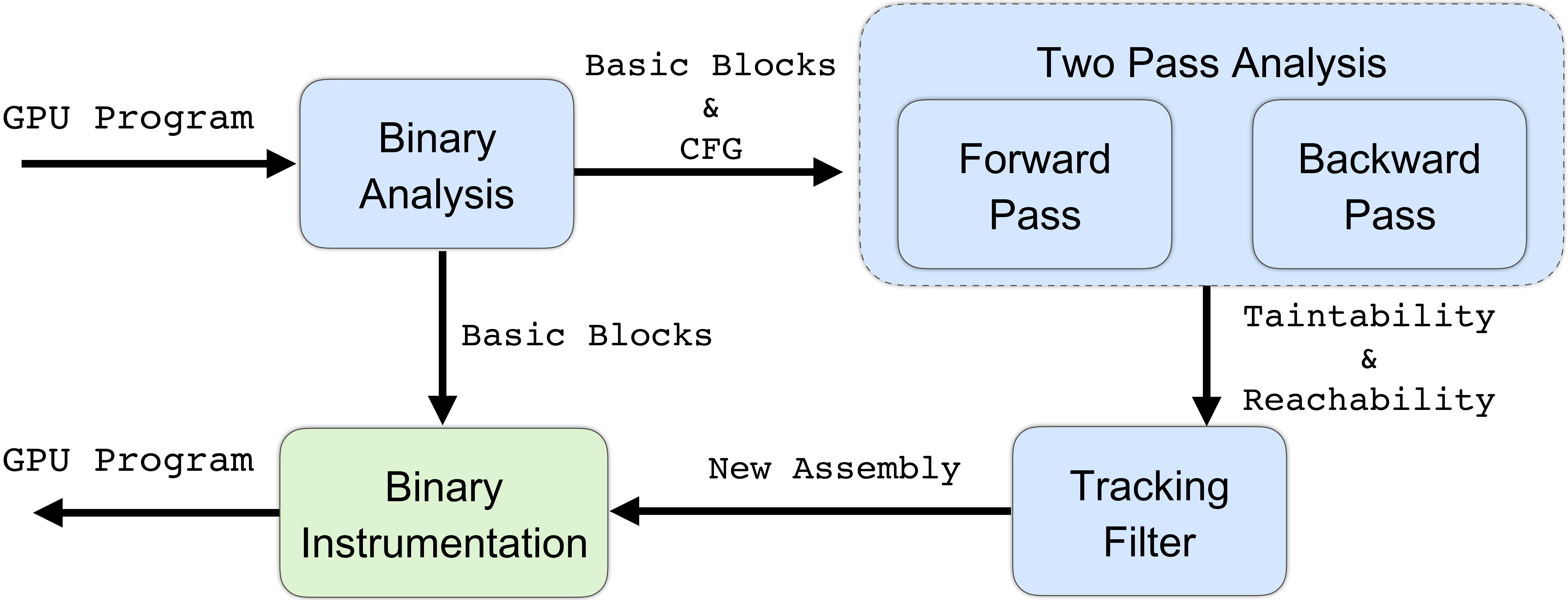
Our Taint Tracking System



Efficient Taint Map

- Taint map is typically kept completely in RAM.
- Off-chip memory is very slow on the GPU.
- Better to keep part of the taint map in on-chip memory.
  - We keep register taintedness in the register file.
  - Registers are 32 bits, so every 32 tracked registers adds only one register of overhead.

5 Evaluation

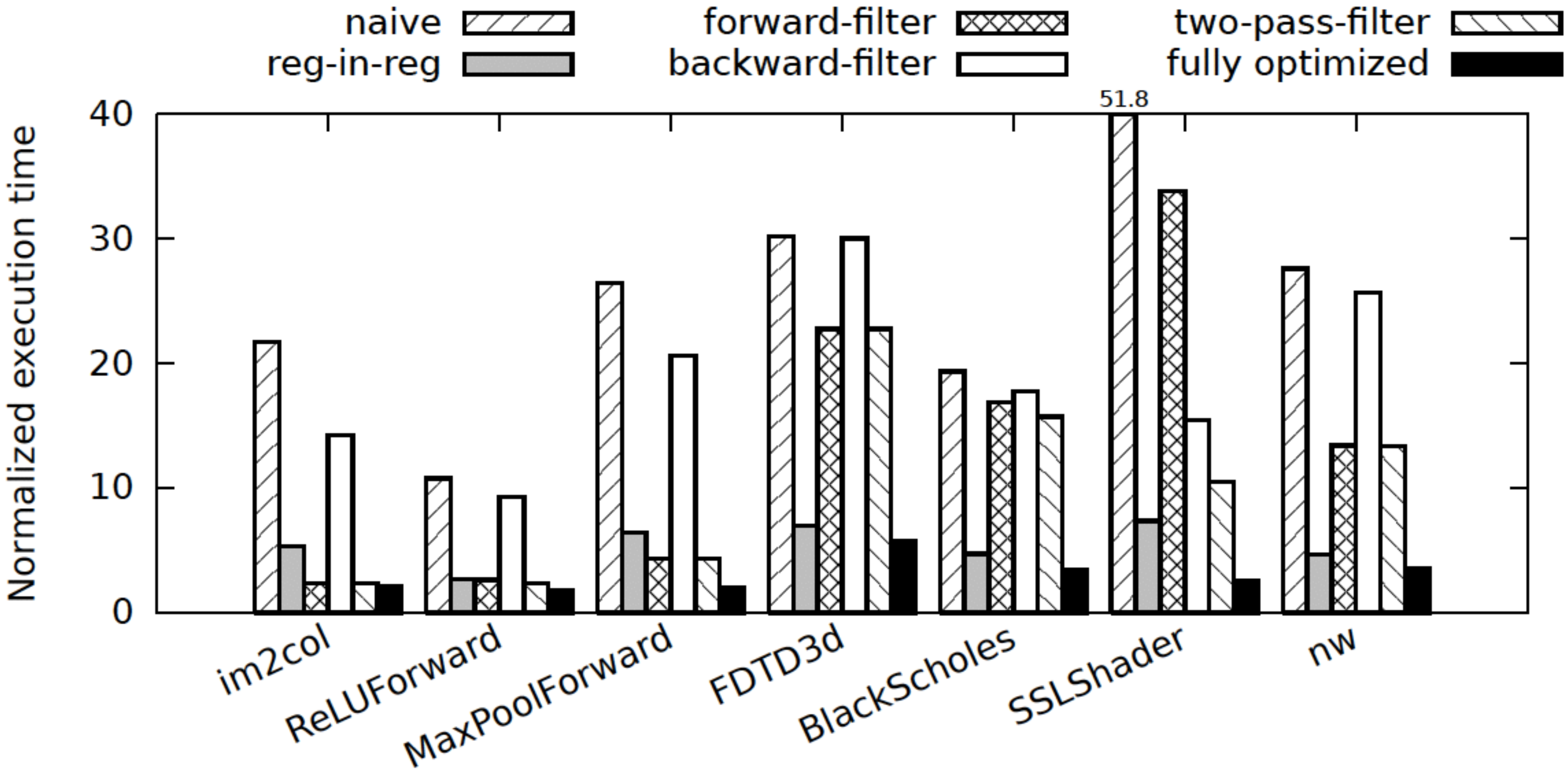
Methodology

- Binary code is converted to assembly with **cuobjdump**.
- Our compiler **Orion** analyzes assembly and adds taint tracking (and erasure) code to assembly
- New assembly is converted into binary based on **asfermi** & **MaxAs**.
- Taint map allocation can be done indirectly through CPU, using LD_PRELOAD to intercept cudaMalloc calls.
- Evaluated on NVIDIA **GTX 745**, compute capability 5.0.

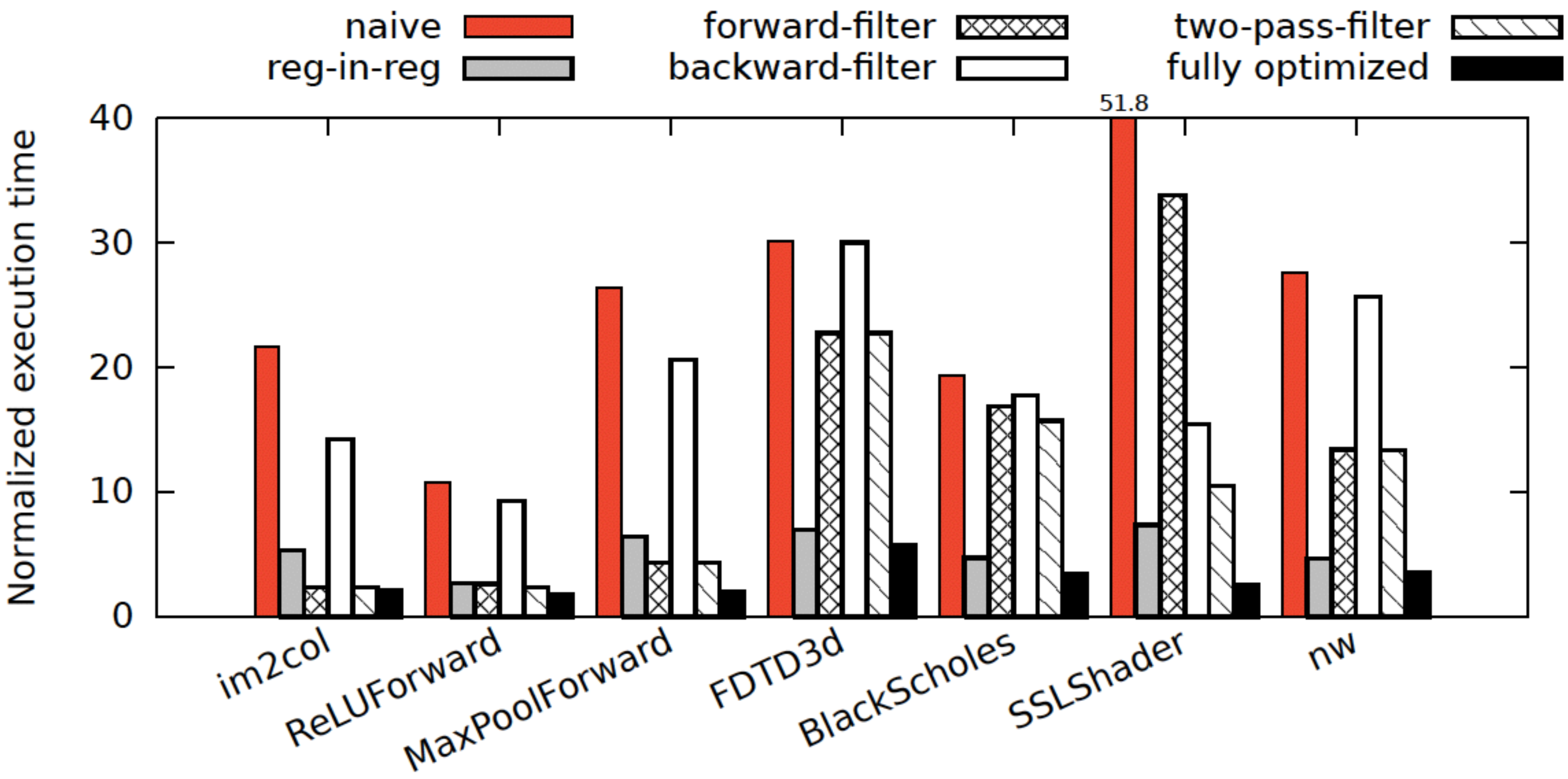
Benchmarks

Benchmark	Domain	Source
im2col	Machine Learning	Caffe
ReLUForward	Machine Learning	Caffe
MaxPoolForward	Machine Learning	Caffe
FDTD3d	Numerical Analysis	CUDA SDK
BlackScholes	Financial Analysis	CUDA SDK
SSLShader	Cryptography	[Jang+, NSDI 2011]
needle	Bioinformatics	Rodinia

Results - Runtime with Tracking

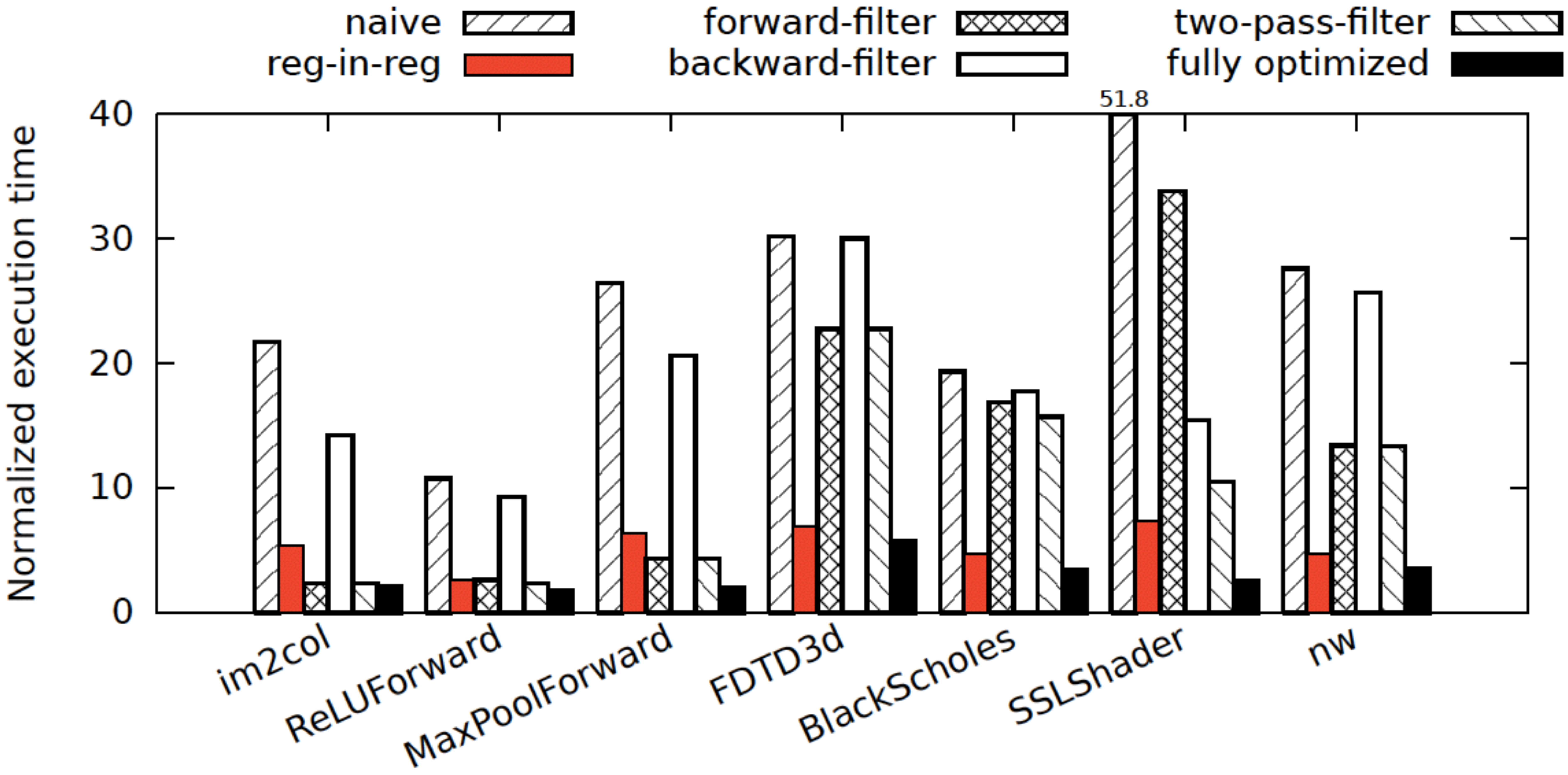


Results - Runtime with Tracking



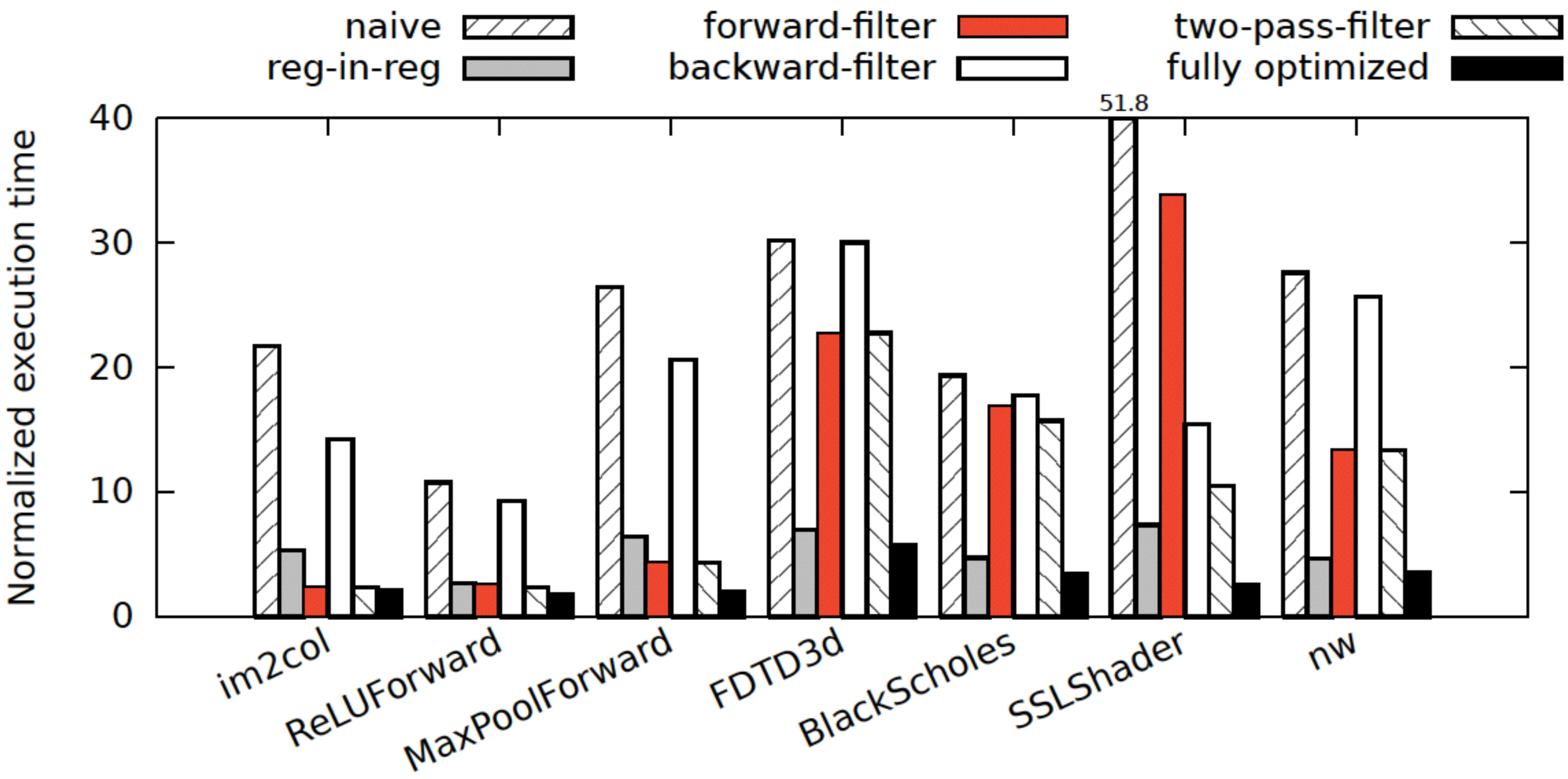
GEOMEAN IS 24.41X

Results - Runtime with Tracking



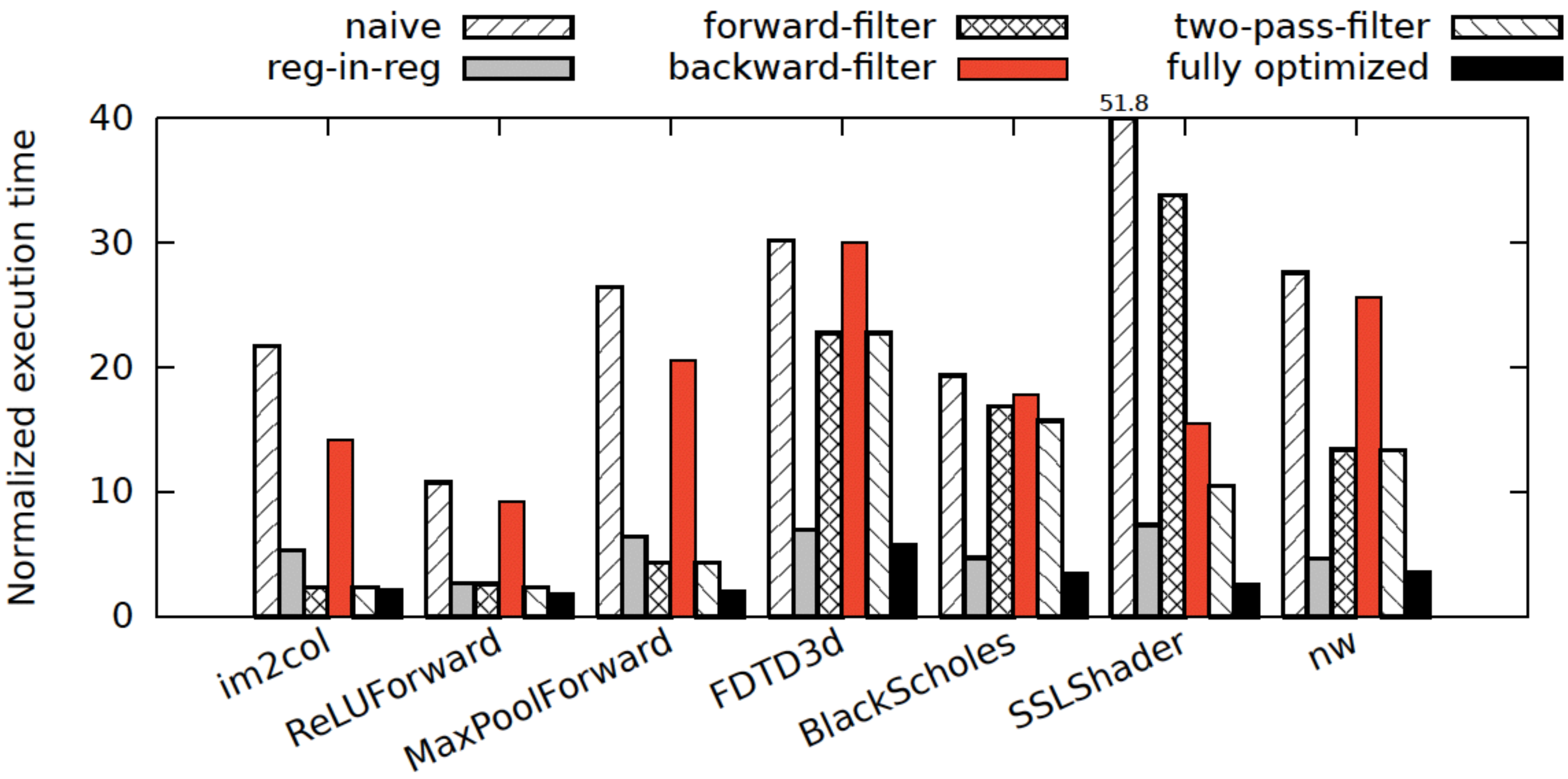
Geomean is 5.19X

Results - Runtime with Tracking



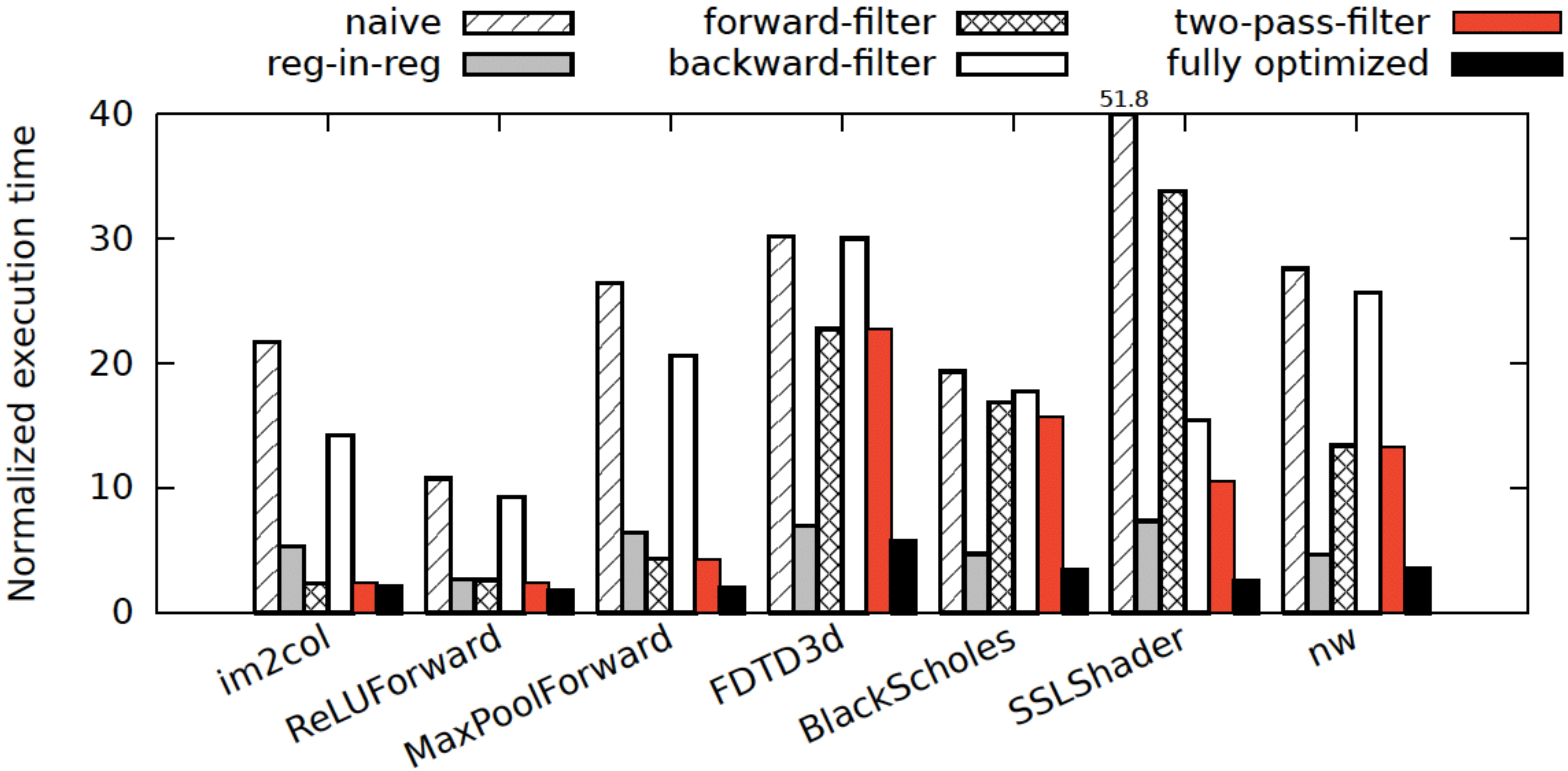
GEOMEAN IS 8.96X

Results - Runtime with Tracking



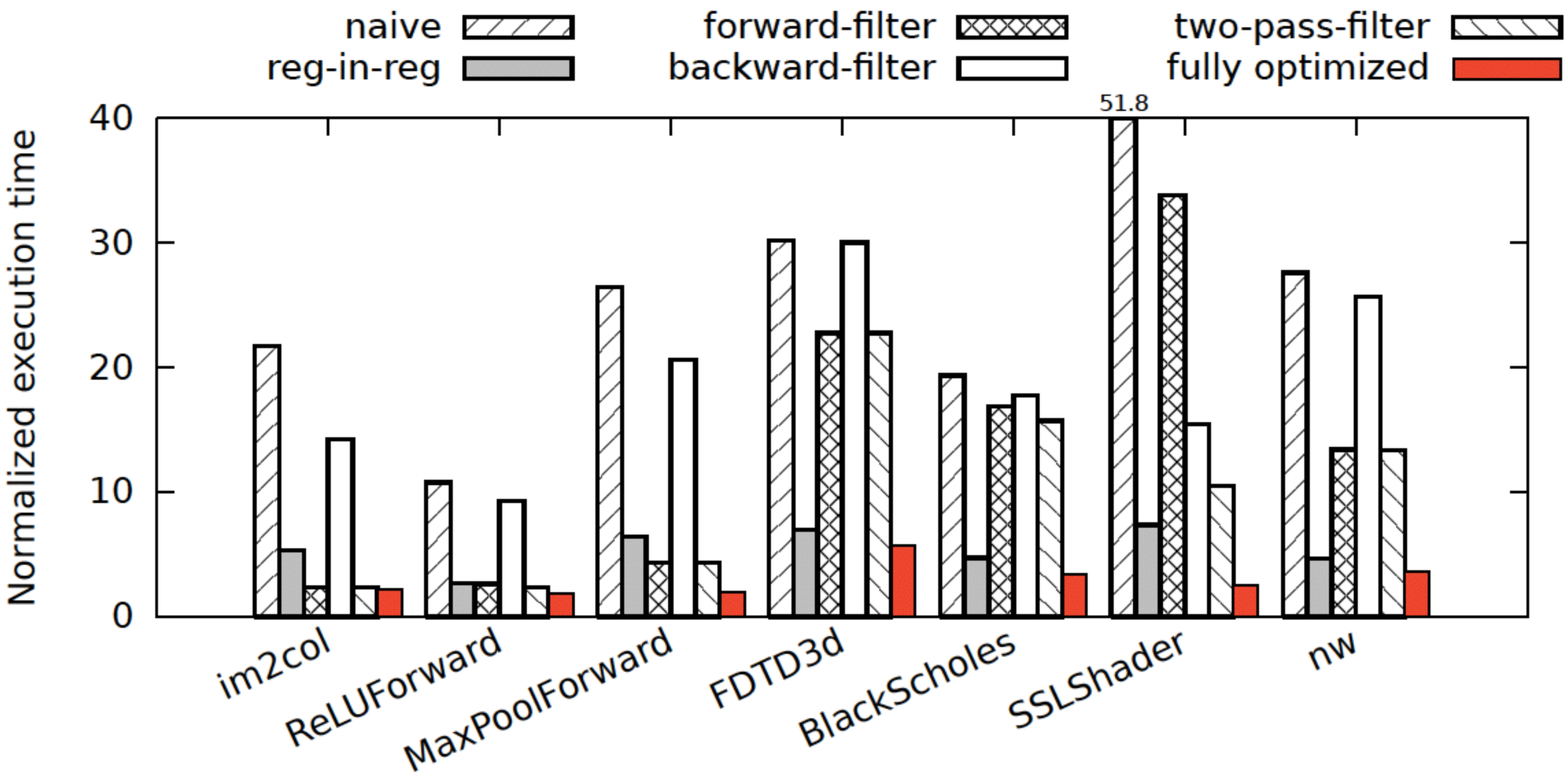
Geomean is 17.84X

Results - Runtime with Tracking



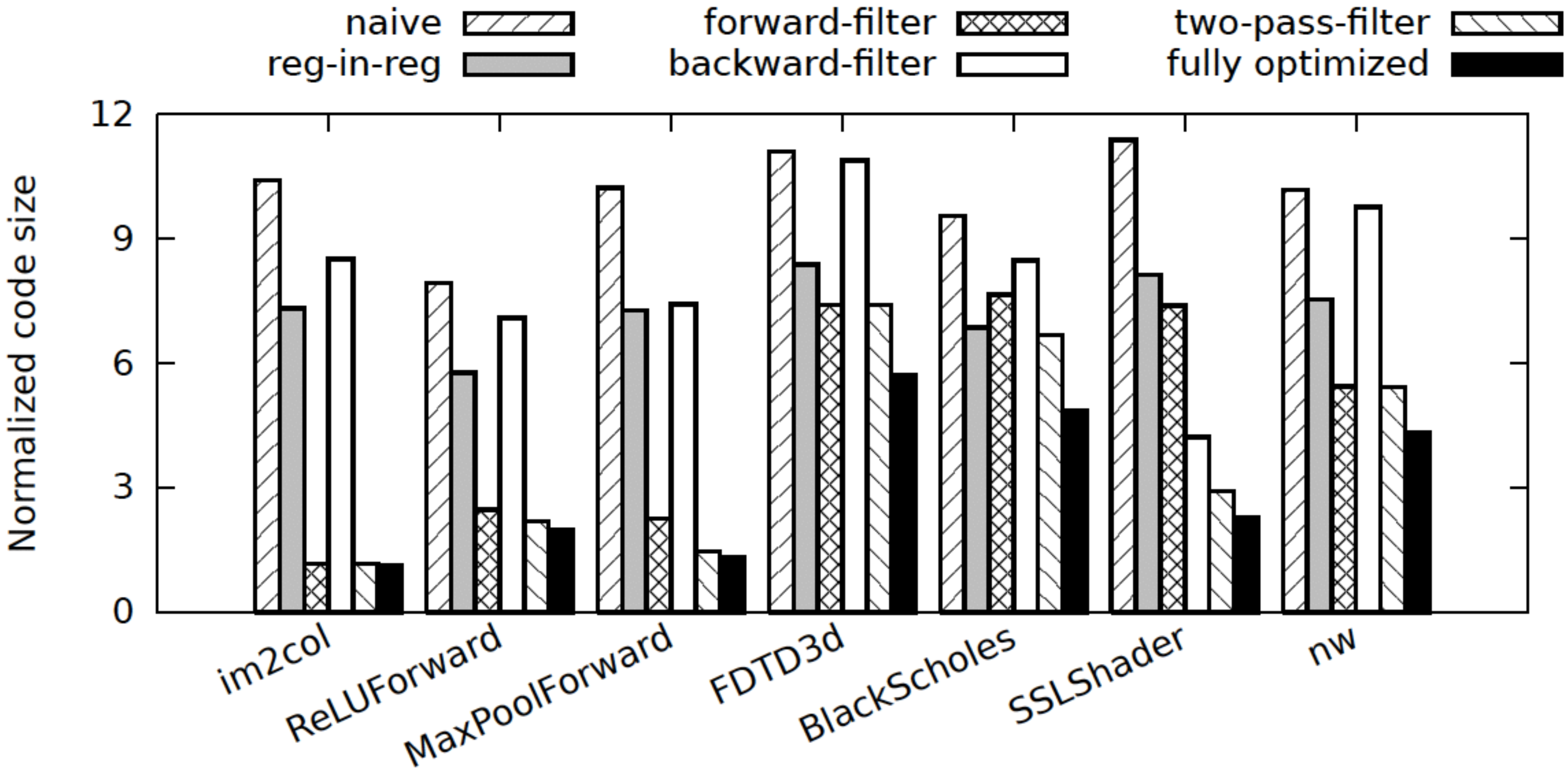
Geomean is 7.38X

Results - Runtime with Tracking



Geomean is 2.80X

Results - Code Size with Tracking



Memory Erasure

- After adding tracking code, we can also add erasure code.
    - On-chip memory can only be reliably erased via binary instrumentation.
    - We have GPU threads clear their own registers and shared memory, as well as thread-private data in local memory.
    - The final taint map identifies global memory with sensitive data, so that it can be erased.

On-Chip & Thread-Private Erasure

Benchmark	Memories	Slowdown
im2col	Reg	0.26%
ReLUForward	Reg	0.33%
MaxPoolForward	Reg	0.59%
FDTD3d	Reg, Shared	5.10%
BlackScholes	Reg	0.40%
SSLShader	Reg, Local	0.41%
needle	Reg, Shared	13.05%

Naive erasure is up to nine times slower!

7 Conclusion

Conclusion

- We present the first GPU dynamic taint tracking system.
    - Two pass filtering eliminates tracking code.
    - GPU-specific optimizations to minimize overhead.
    - Clears memory the programmer cannot.
    - Improves tracking performance by 5X to 20X.

7

Questions?