Efficient Context Switching for the Stack Cache: Implementation and Analysis

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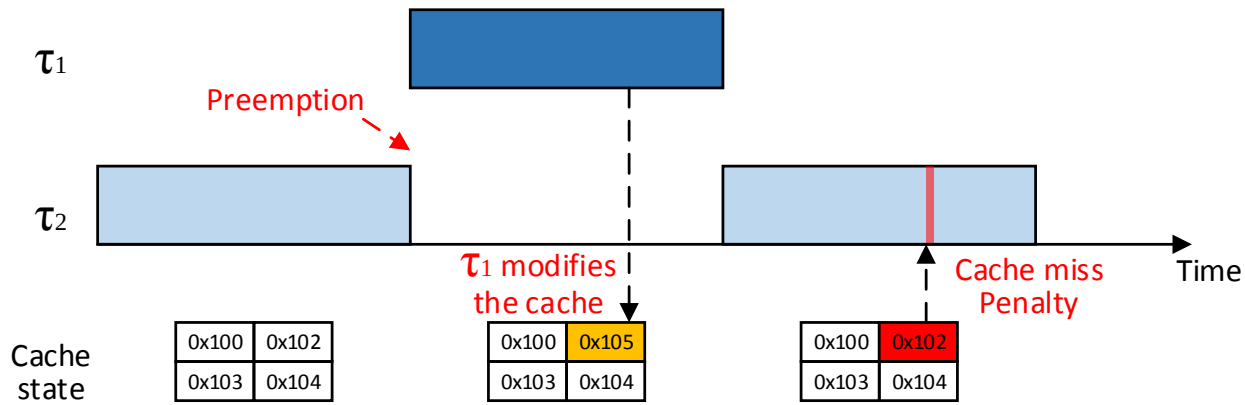
Cache Related Preemption Delay - On Standard Caches

Cache Related Preemption Delay (CRPD): Time penalty introduced by cache misses due to task preemption.



- Preempting task may evict cache blocks of a preempted task.
- Cache misses may occur when the preempted task is resumed.

What is a Stack Cache?

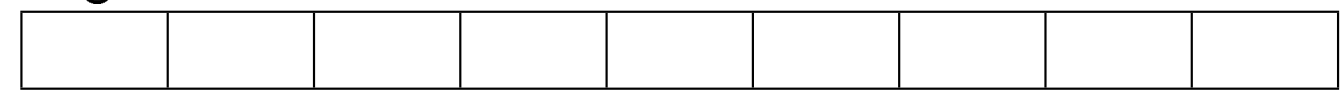
Dedicated cache for stack data

- Simple ring buffer
- All stack accesses are guaranteed hits (no need to analyze them)
- Dedicated stack control instructions (need to be analyzed)
  - `sres` x: reserve x blocks on the stack
  - `sfree` x: free x blocks on the stack
  - `sens` x: ensure that at least x blocks are cached
- Intuitively: a cache window following the stack top

Example: Stack Cache

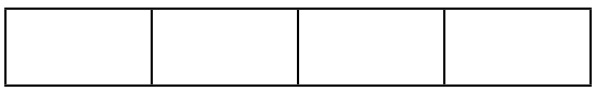
```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3
sens 2              sens 2
sfree 2             sfree 2
```

Logical stack



MT ST

Stack cache*



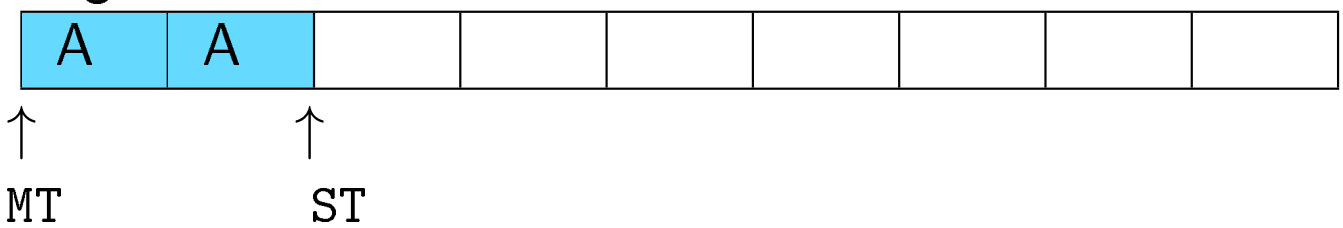
Occupancy = 0

*Cache configuration: 4 blocks

Example: Stack Cache

```
function A()        function B()        function C()
sres 2  ←           sres 2              sres 3
call B()            call C()            sfree 3
sens 2              sens 2
sfree 2             sfree 2
```

Logical stack



Stack cache*

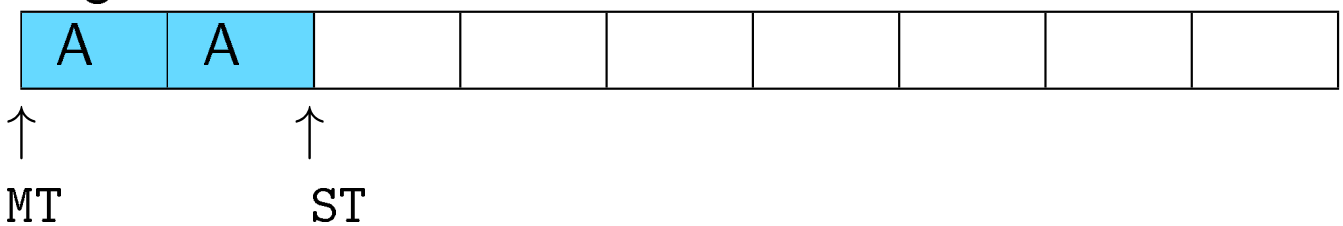
Occupancy = 2

*Cache configuration: 4 blocks

Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B() ←          call C()            sfree 3
sens 2              sens 2
sfree 2             sfree 2
```

Logical stack



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Example: Stack Cache

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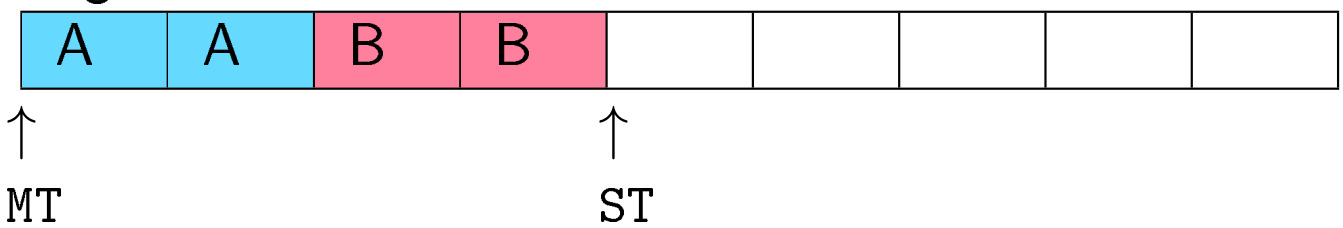

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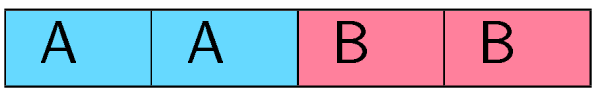

Occupancy = 4

*Cache configuration: 4 blocks

Example: Stack Cache

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function A()        function B()        function C()
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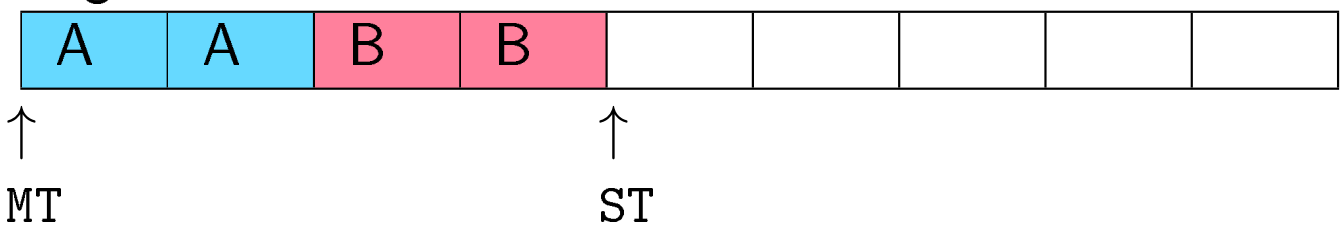
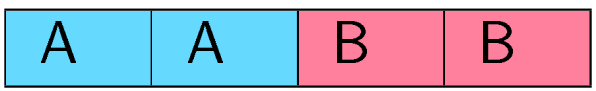
Logical stack



Stack cache*



Occupancy = 4

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Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3  ←
call B()            call C()            sfree 3
sens 2              sens 2
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```
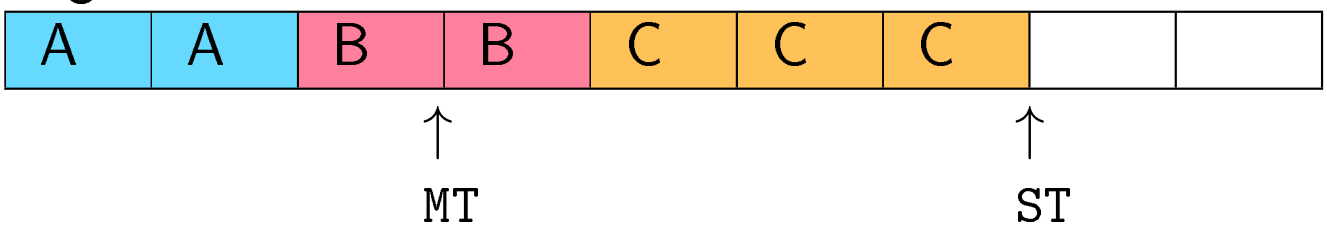

Logical stack



Stack cache*

Spill 3 blocks

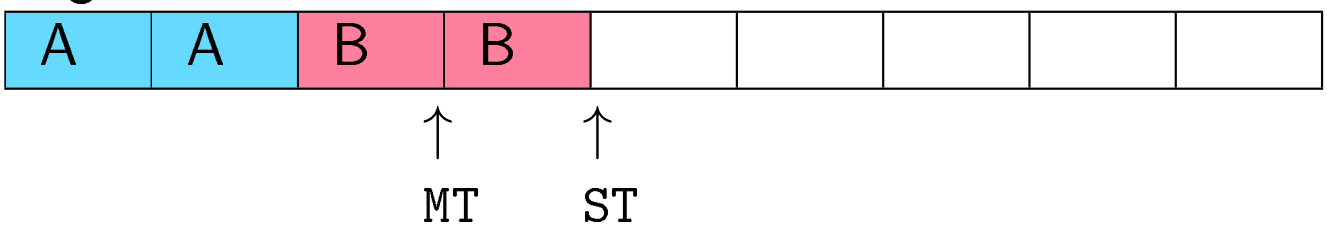
Occupancy = 4

*Cache configuration: 4 blocks

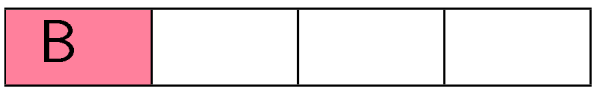
Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3 ←
sens 2              sens 2
sfree 2             sfree 2
```

Logical stack



Stack cache*



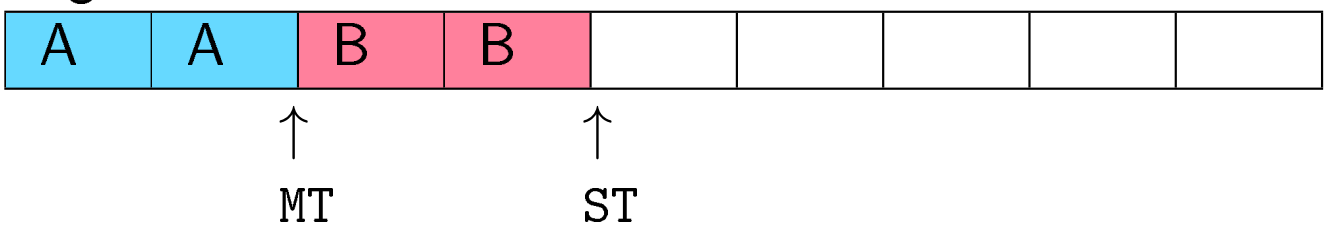
Occupancy = 1

*Cache configuration: 4 blocks

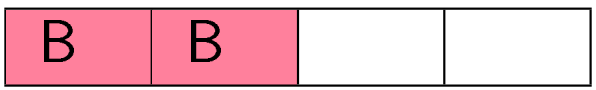
Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3
sens 2              sens 2  ←
sfree 2             sfree 2
```

Logical stack



Stack cache*



Fill 1 block

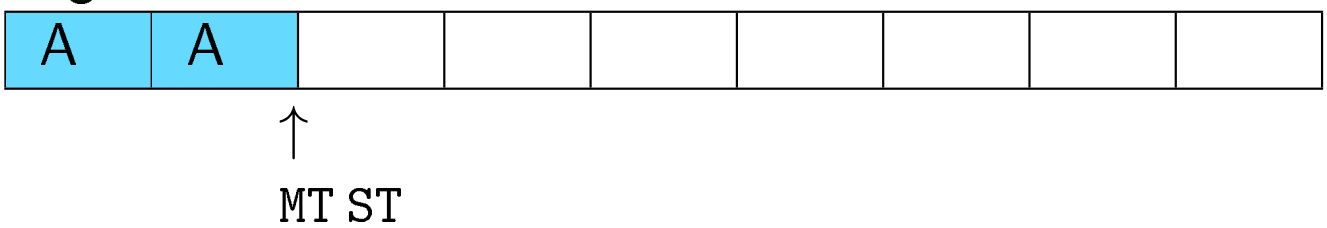
Occupancy = 2

*Cache configuration: 4 blocks

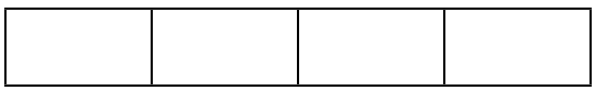
Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3
sens 2              sens 2
sfree 2             sfree 2 ←
```

Logical stack



Stack cache*



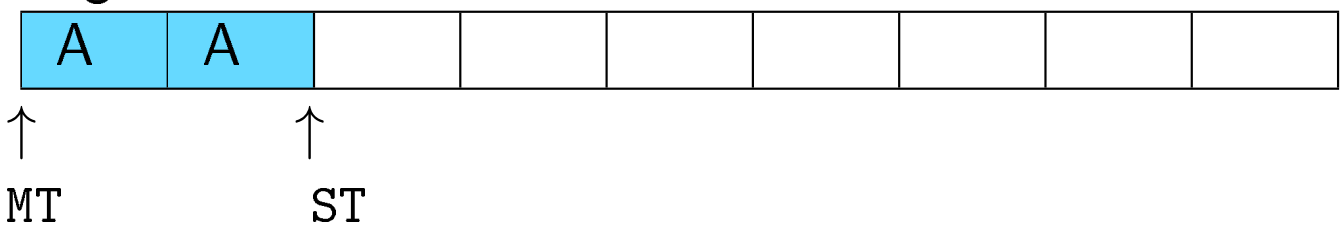
Occupancy = 0

*Cache configuration: 4 blocks

Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3
sens 2  ←           sens 2
sfree 2             sfree 2
```

Logical stack



Stack cache*

Fill 2 blocks

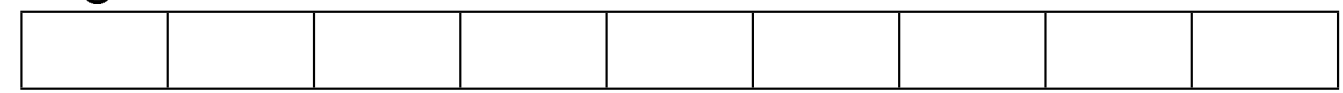
Occupancy = 2

*Cache configuration: 4 blocks

Example: Stack Cache

```
function A()        function B()        function C()
sres 2              sres 2              sres 3
call B()            call C()            sfree 3
sens 2              sens 2
sfree 2 ←           sfree 2
```

Logical stack



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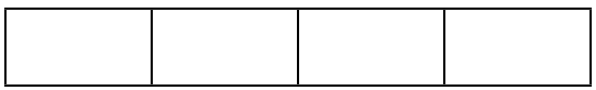
Stack cache*



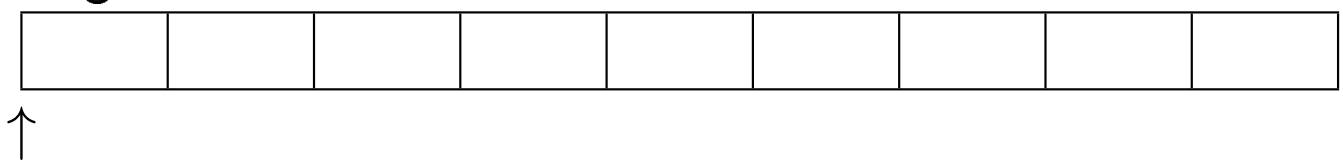
Occupancy = 0

*Cache configuration: 4 blocks

Example: Stack Cache

```
function A()        function B()        function C()
sres 2 ⟨0⟩          sres 2 ⟨0⟩          sres 3 ⟨3⟩
call B()            call C()            sfree 3
sens 2 ⟨2⟩          sens 2 ⟨1⟩
sfree 2             sfree 2
```

Logical stack



MT ST

Stack cache*

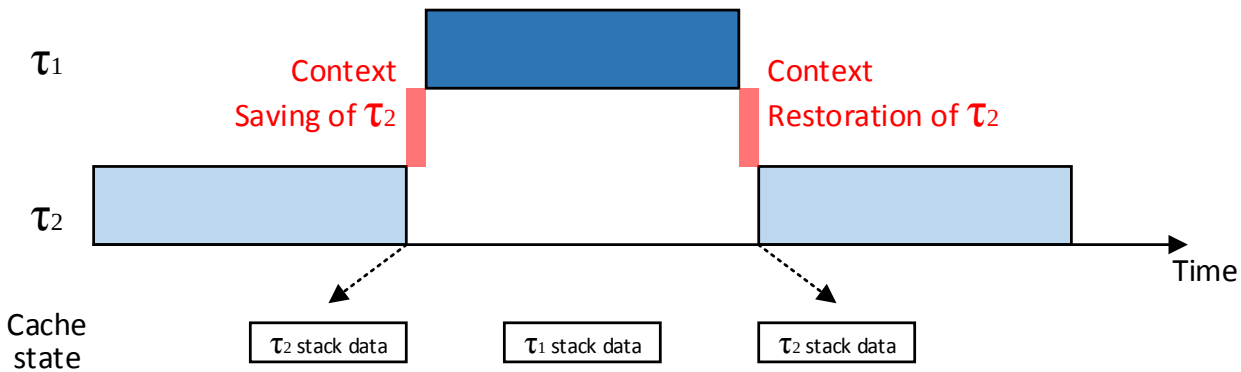
Bounds ⟨#⟩ provided by *standard* Stack Cache Analysis (no preemption)

*Cache configuration: 4 blocks

Context Switching - On Stack Cache

Due to its simplicity, the stack cache cannot be shared among tasks.

$\Rightarrow$ Context of preempted task has to be saved/restored.



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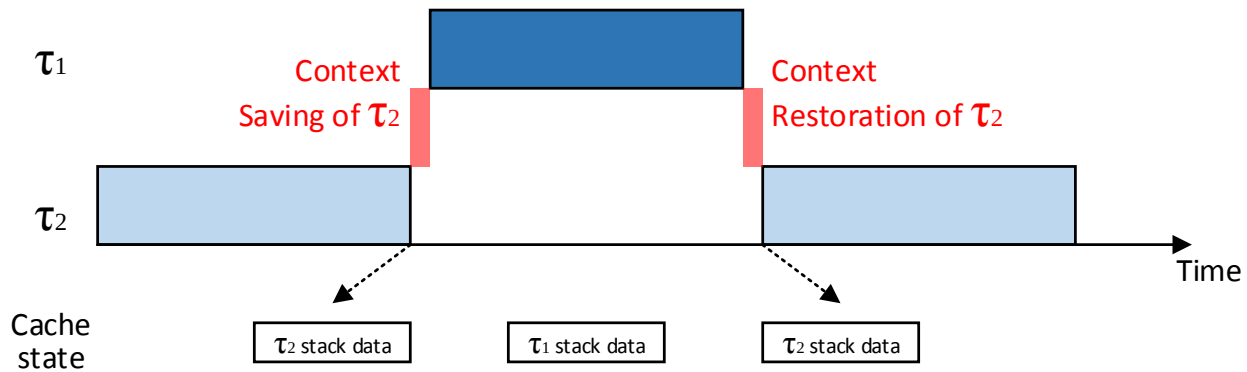

Main questions:

- Which cache blocks have to be saved/restored?
- What is the impact on the worst-case behavior after the preemption?

Motivational Example

```
(i_1^A) func A()
(i_2^A)  sres 2 ⟨0⟩
(i_3^A)  B()
(i_4^A)  sens 2 ⟨2⟩
(i_5^A)  sfree 2
```

```
(i_1^B) func B()
(i_2^B)  sres 2 ⟨0⟩
(i_3^B)  nop ↯
(i_4^B)  C()
(i_5^B)  sens 2 ⟨1⟩
(i_6^B)  sfree 2
```

```
(i_1^C) func C()
(i_2^C)  sres 3 ⟨3⟩
(i_3^C)  sfree 3
```

Motivational Example

```
(i1A) func A()
(i2A)   sres 2 ⟨0⟩
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(i4A)   sens 2 ⟨2⟩
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```
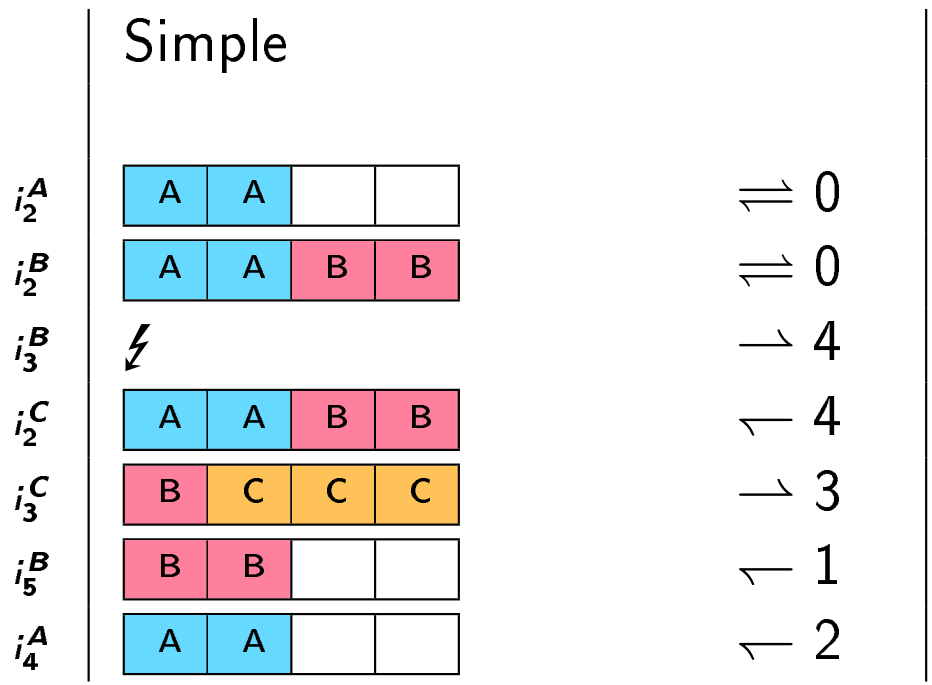

```
(i1B) func B()
(i2B)   sres 2 ⟨0⟩
(i3B)   nop ↯
(i4B)   C()
(i5B)   sens 2 ⟨1⟩
(i6B)   sfree 2
```

```
(i1C) func C()
(i2C)   sres 3 ⟨3⟩
(i3C)   sfree 3
```



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```
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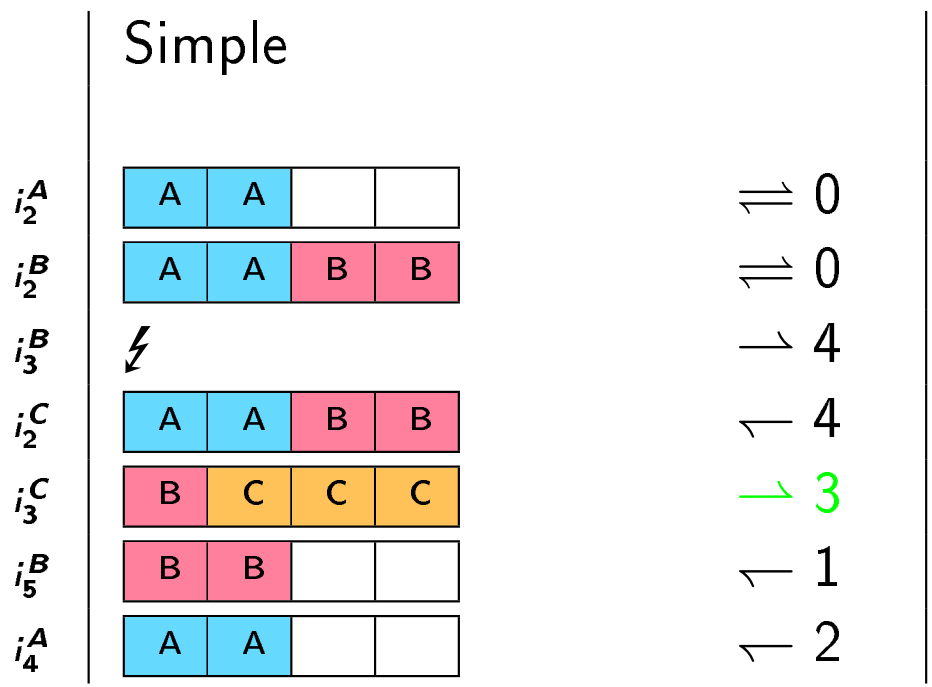

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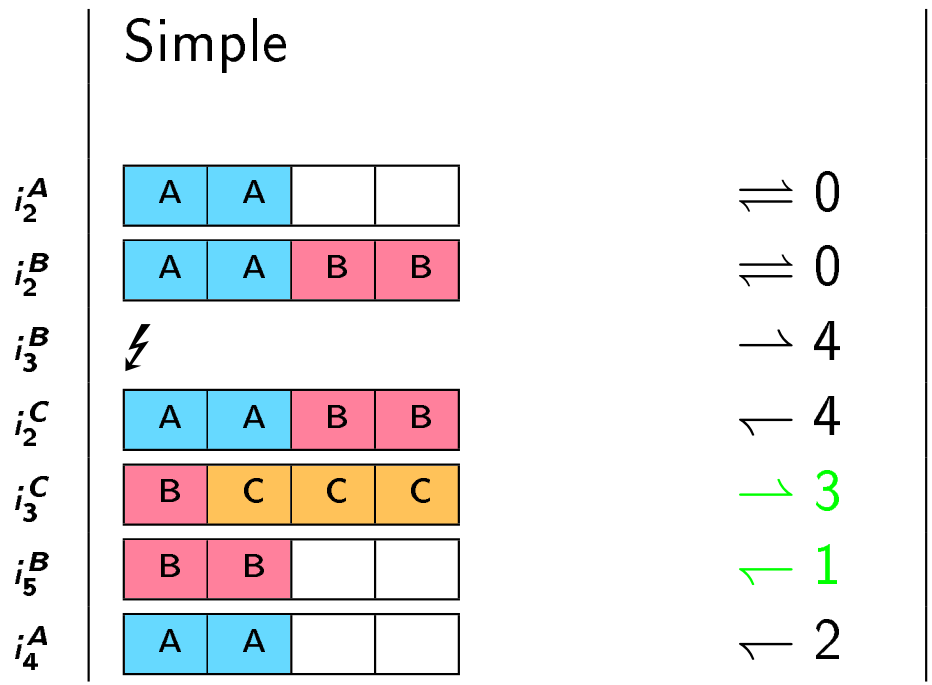

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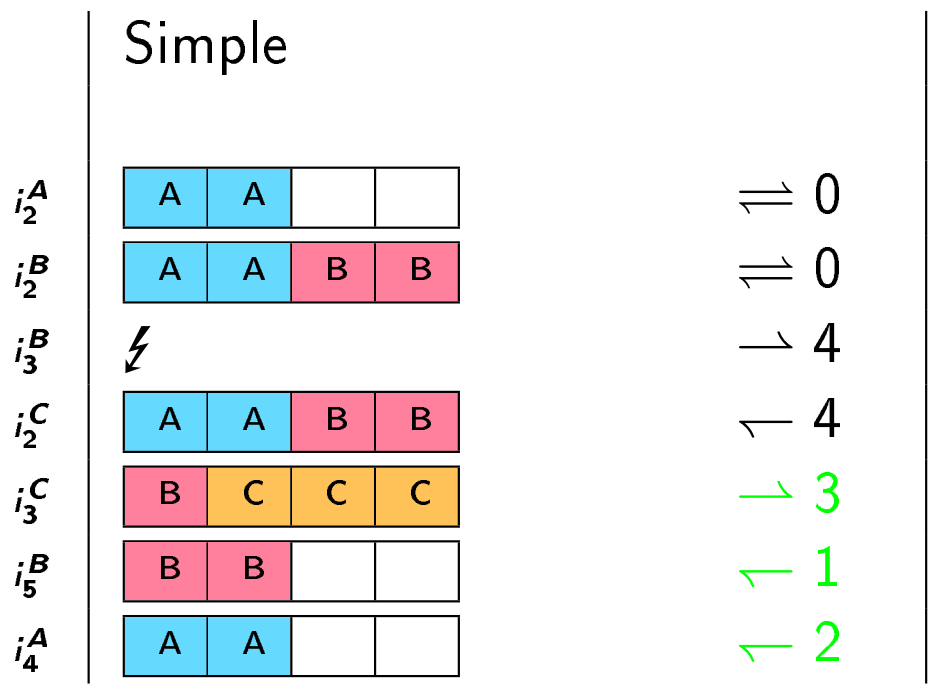

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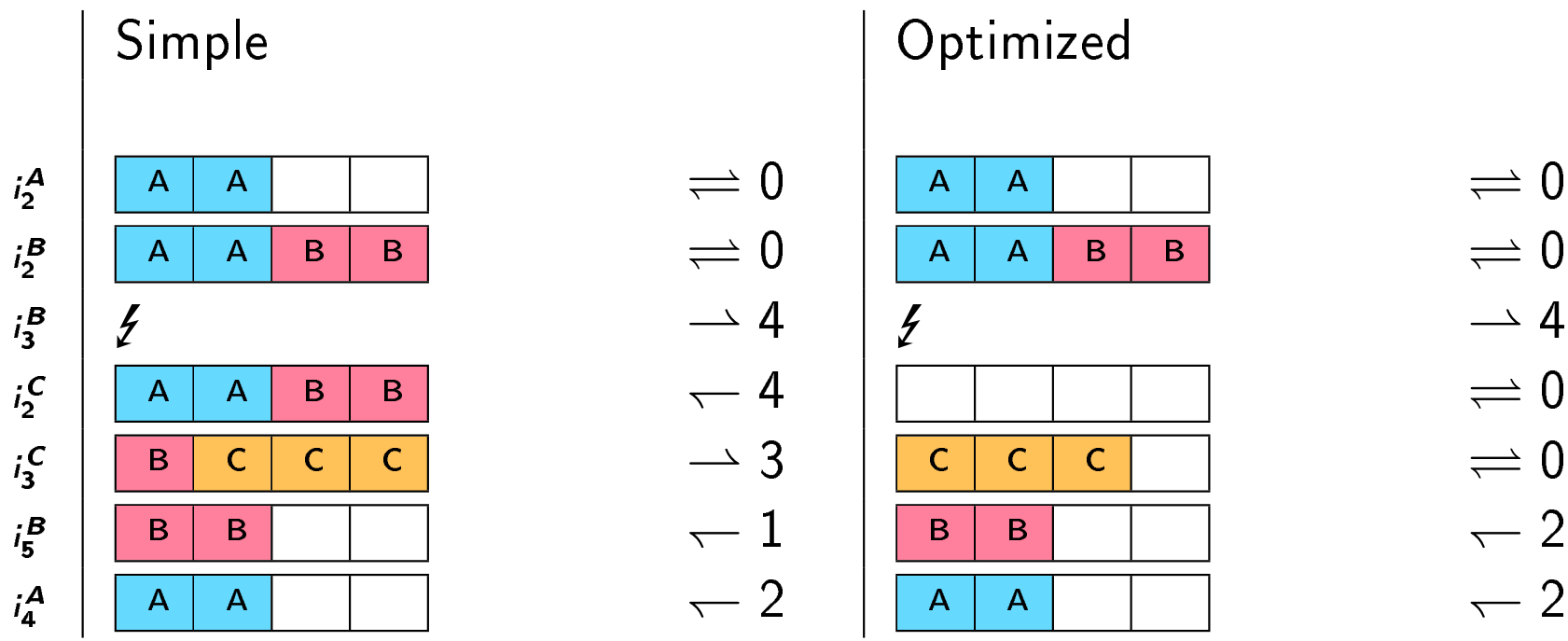

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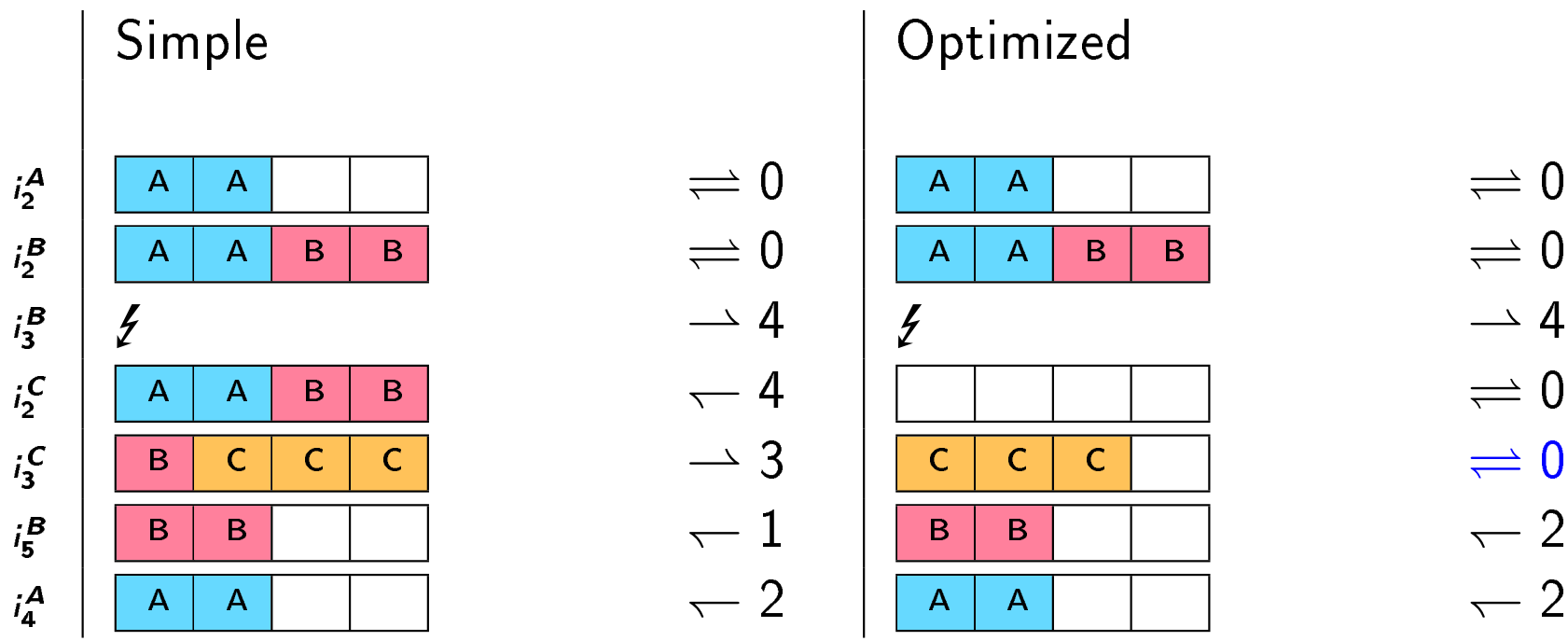

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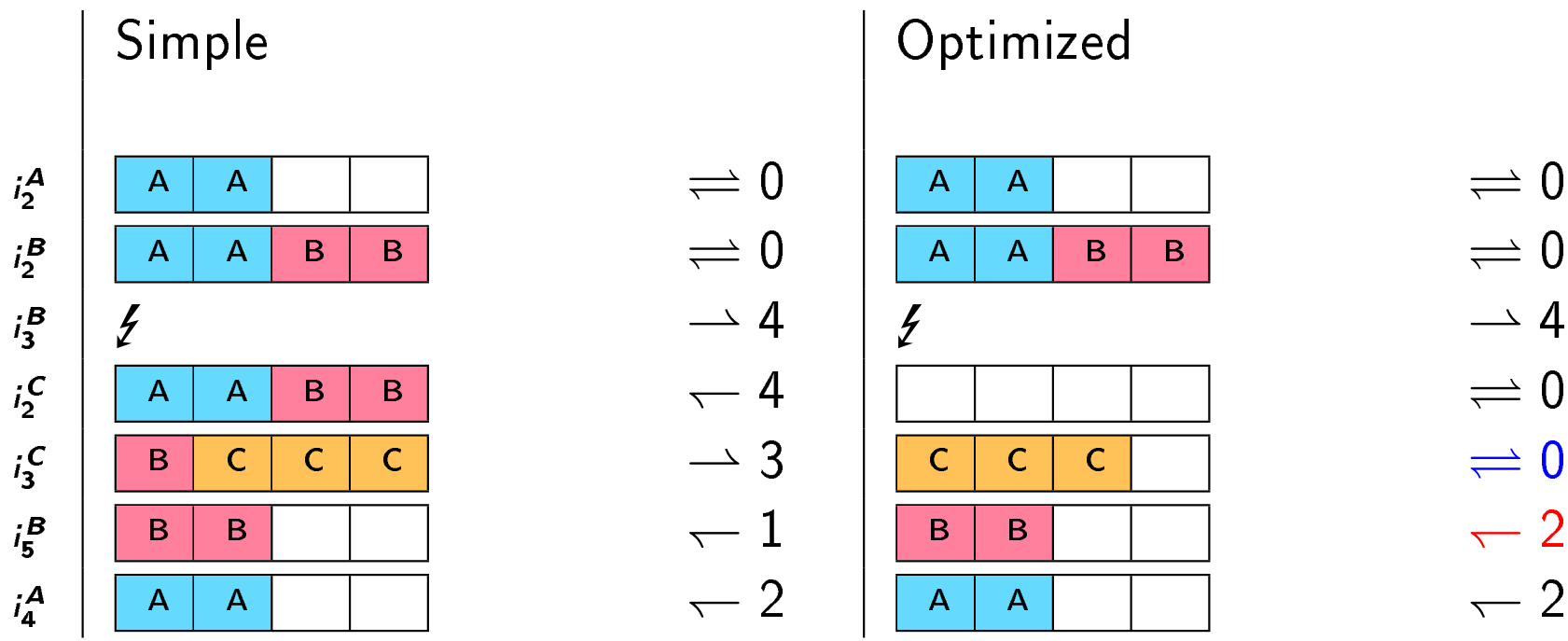

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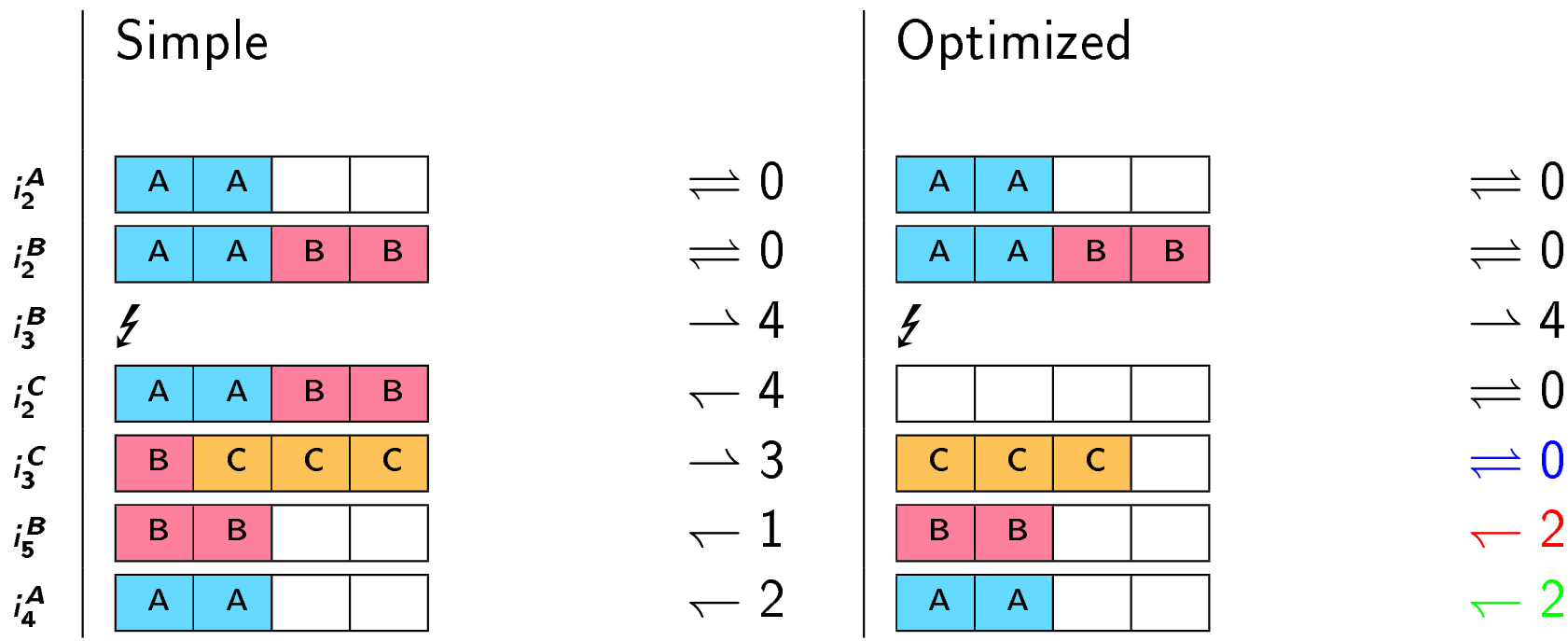
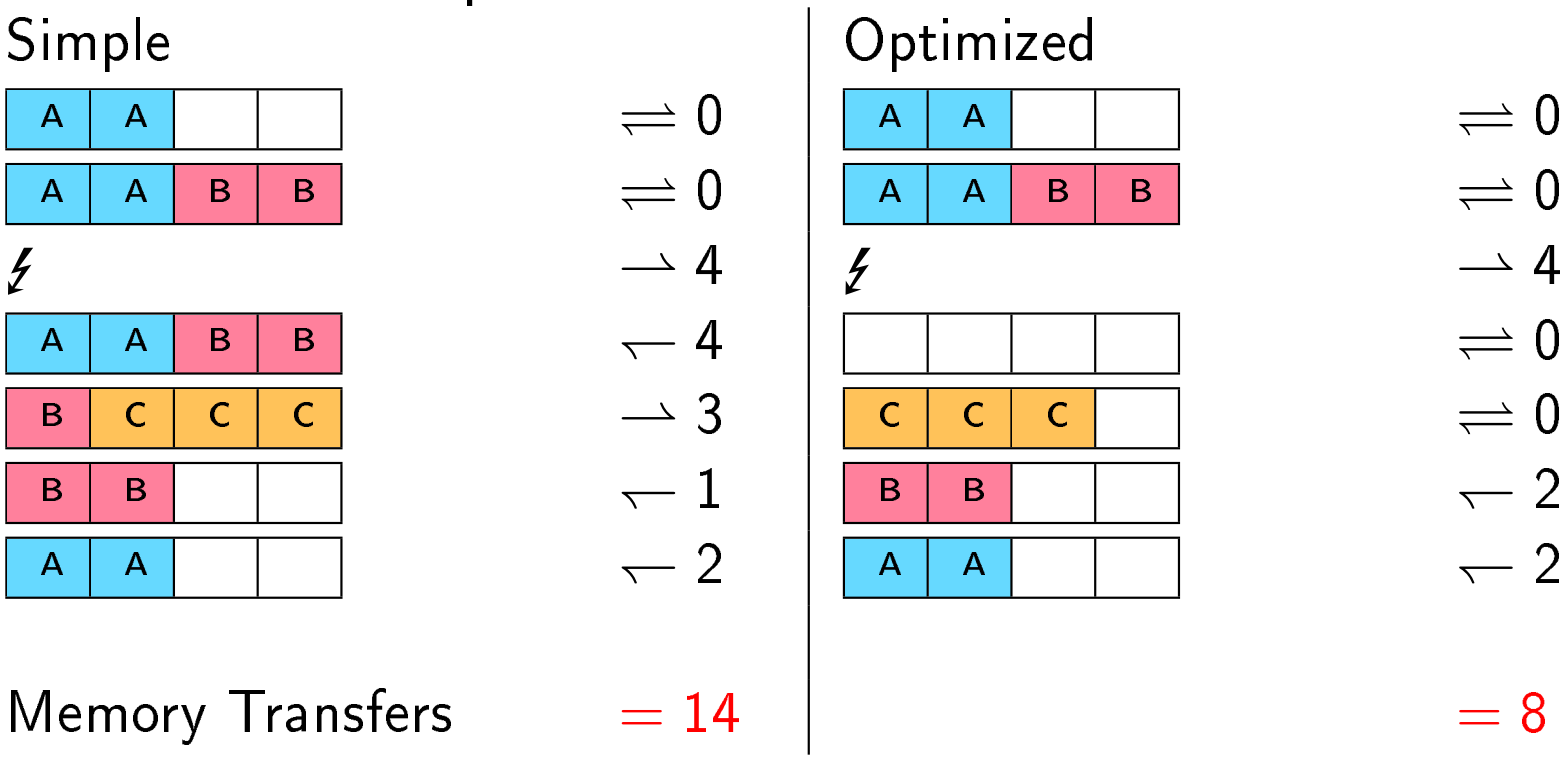


Motivational Example



Optimized approach : Potentially fewer memory transfers, but worst-case behavior has to be re-analyzed.

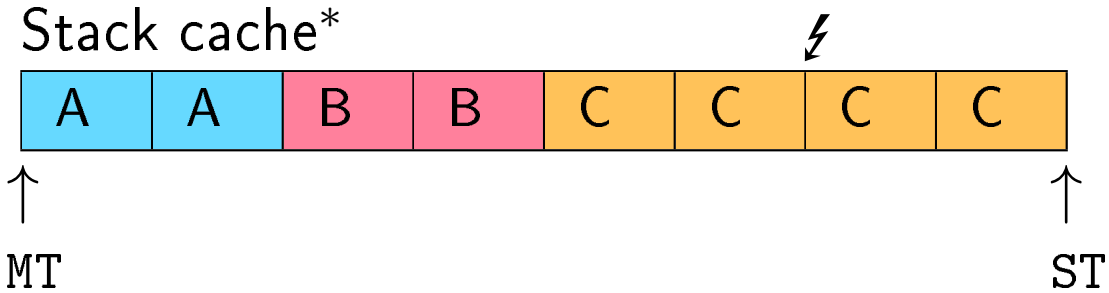
Two analysis problems :

- Context Saving Analysis (CSA)
- Context Restoring Analysis (CRA)

Context Saving Analysis (CSA)

Split the stack cache into three regions by introducing two pointers:

- Lazy Pointer (LP) keeps track of coherent data.
  - Analysis introduced in previous work.
- Dead Pointer (DP) keeps track of certainly dead data.
  - Using data-flow analysis (livness analysis).



*Cache configuration: 8 blocks

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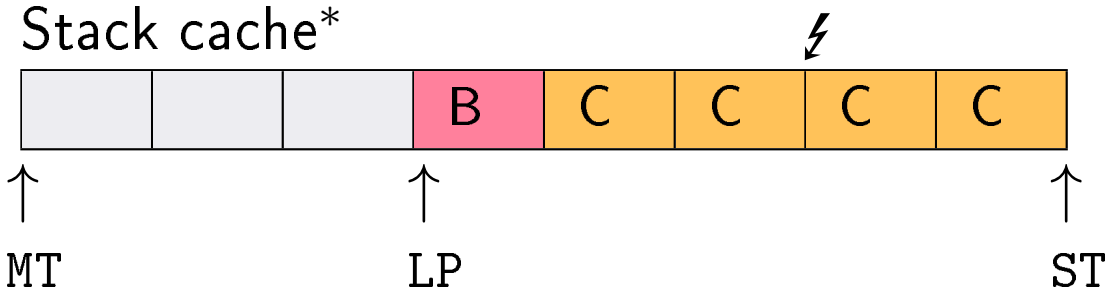

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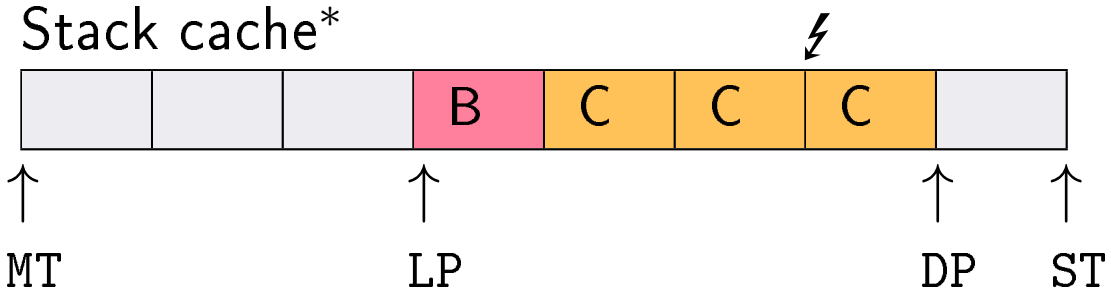
- Dead Pointer (DP) keeps track of certainly dead data.
  - Using data-flow analysis (livness analysis).

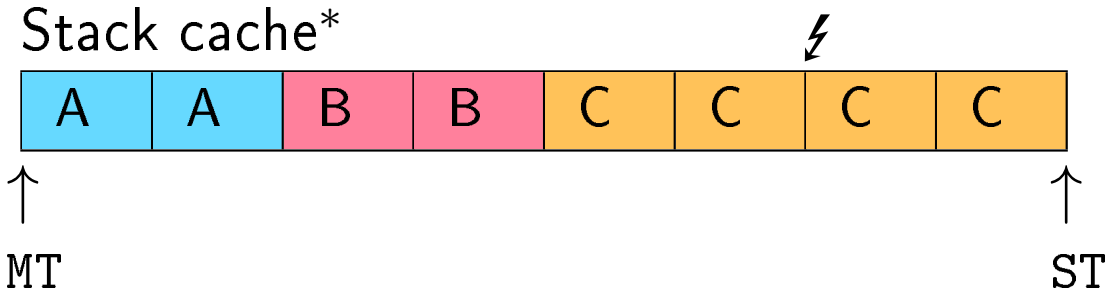


*Cache configuration: 8 blocks

Context Restoring Analysis (CRA)

Split the stack cache into three regions introducing two pointers.

- Restore Pointer (RP) keeps track of data that has to be restored explicitly. Excluding :
  - Stack frames of calling functions.
  - Local data that will be ensured.
  - Analyzed using data-flow analysis (similar to liveness)
- Global analysis of gains at reserves.
- Global analysis of additional costs at ensures.



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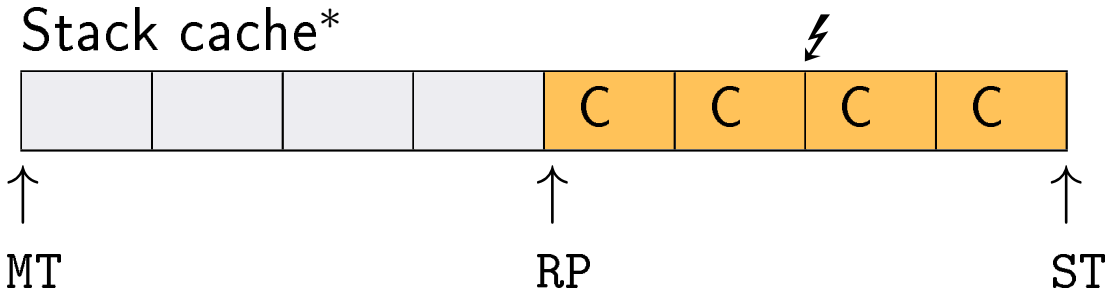

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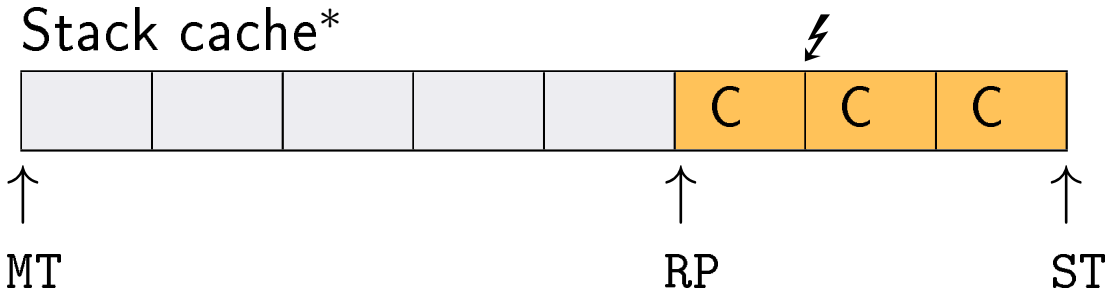

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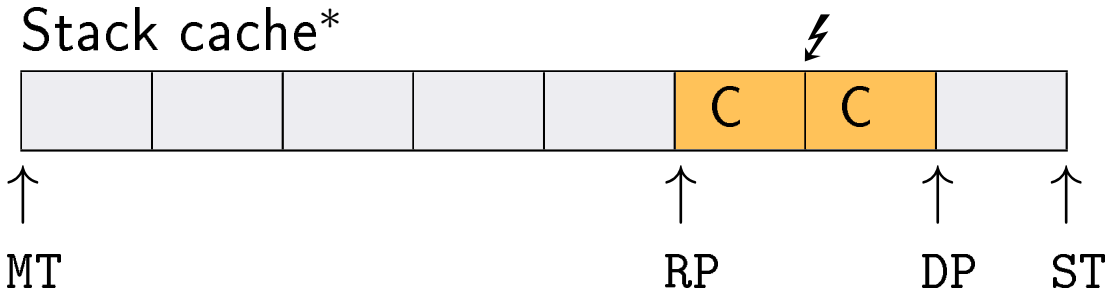

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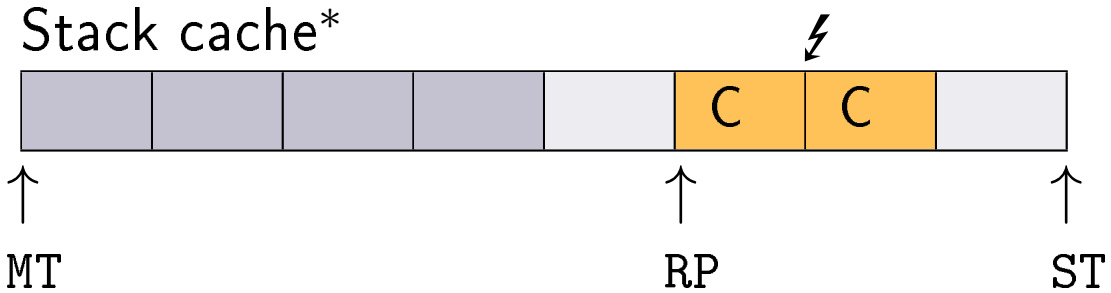

*Cache configuration: 8 blocks

Global Cost of Ensure Instruction

- `sens` instructions partially restore stack frames for free*.
- We need to account for the additional costs.

```
(i1^A) func A()
(i2^A)   sres 2 ⟨0⟩
(i3^A)   B()
(i4^A)   sens 2 ⟨2⟩
(i5^A)   sfree 2
```

```
(i1^B) func B()
(i2^B)   sres 2 ⟨0⟩
(i4^B)   C()
(i5^B)   sens 2 ⟨1⟩
(i6^B)   sfree 2
```

```
(i1^C) func C()
(i2^C)   sres 3 ⟨3⟩
(i3^C)   nop ↯
(i4^C)   sfree 3
```

*For free : already taken into account by the standard Stack Cache Analysis.

Global Analysis of Ensure Cost - Example

```
(i_1^A) func A()
(i_2^A)   sres 2 ⟨0⟩
(i_3^A)   B()
(i_4^A)   sens 2 ⟨2⟩
(i_5^A)   sfree 2
```

```
(i_1^B) func B()
(i_2^B)   sres 2 ⟨0⟩
(i_4^B)   C()
(i_5^B)   sens 2 ⟨1⟩
(i_6^B)   sfree 2
```

```
(i_1^C) func C()
(i_2^C)   sres 3 ⟨3⟩
(i_3^C)   nop ↯
(i_4^C)   sfree 3
```

Global Analysis of Ensure Cost - Example

```
(i_1^A) func A()
(i_2^A)  sres 2 ⟨0⟩
(i_3^A)  B()
(i_4^A)  sens 2 ⟨2⟩
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```
(i_1^B) func B()
(i_2^B)  sres 2 ⟨0⟩
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(i_5^B)  sens 2 ⟨1⟩
(i_6^B)  sfree 2
```
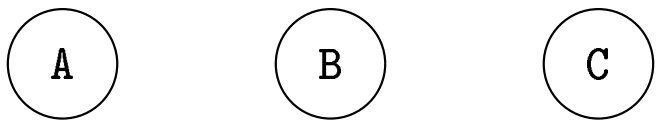

```
(i_1^C) func C()
(i_2^C)  sres 3 ⟨3⟩
(i_3^C)  nop ↯
(i_4^C)  sfree 3
```

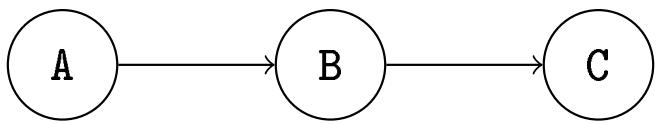


Global Analysis of Ensure Cost - Example

```
(i1A) func A()
(i2A)  sres 2 ⟨0⟩
(i3A)  B()
(i4A)  sens 2 ⟨2⟩
(i5A)  sfree 2
```

```
(i1B) func B()
(i2B)  sres 2 ⟨0⟩
(i4B)  C()
(i5B)  sens 2 ⟨1⟩
(i6B)  sfree 2
```

```
(i1C) func C()
(i2C)  sres 3 ⟨3⟩
(i3C)  nop ↯
(i4C)  sfree 3
```



Global Analysis of Ensure Cost - Example

```
(i1^A) func A()
(i2^A)   sres 2 ⟨0⟩
(i3^A)   B()
(i4^A)   sens 2 ⟨2⟩
(i5^A)   sfree 2
```

```
(i1^B) func B()
(i2^B)   sres 2 ⟨0⟩
(i4^B)   C()
(i5^B)   sens 2 ⟨1⟩
(i6^B)   sfree 2
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```
(i1^C) func C()
(i2^C)   sres 3 ⟨3⟩
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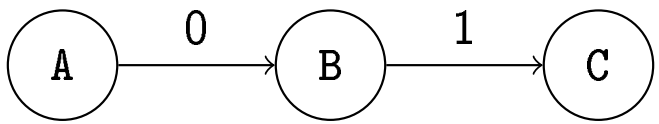
(i4^C)   sfree 3
```



Global Analysis of Ensure Cost - Example

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(i1A) func A()
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(i3A)   B()
(i4A)   sens 2 ⟨2⟩
(i5A)   sfree 2
```
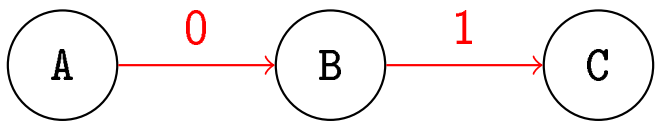
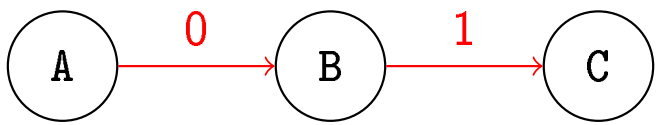

```
(i1B) func B()
(i2B)   sres 2 ⟨0⟩
(i4B)   C()
(i5B)   sens 2 ⟨1⟩
(i6B)   sfree 2
```

```
(i1C) func C()
(i2C)   sres 3 ⟨3⟩
(i3C)   nop ↯
(i4C)   sfree 3
```



Global Analysis of Ensure Cost - Example

```
(i1^A) func A()          (i1^B) func B()          (i1^C) func C()
(i2^A)   sres 2 ⟨0⟩      (i2^B)   sres 2 ⟨0⟩      (i2^C)   sres 3 ⟨3⟩
(i3^A)   B()             (i4^B)   C()            (i3^C)   nop ↯
(i4^A)   sens 2 ⟨2⟩      (i5^B)   sens 2 ⟨1⟩      (i4^C)   sfree 3
(i5^A)   sfree 2         (i6^B)   sfree 2
```



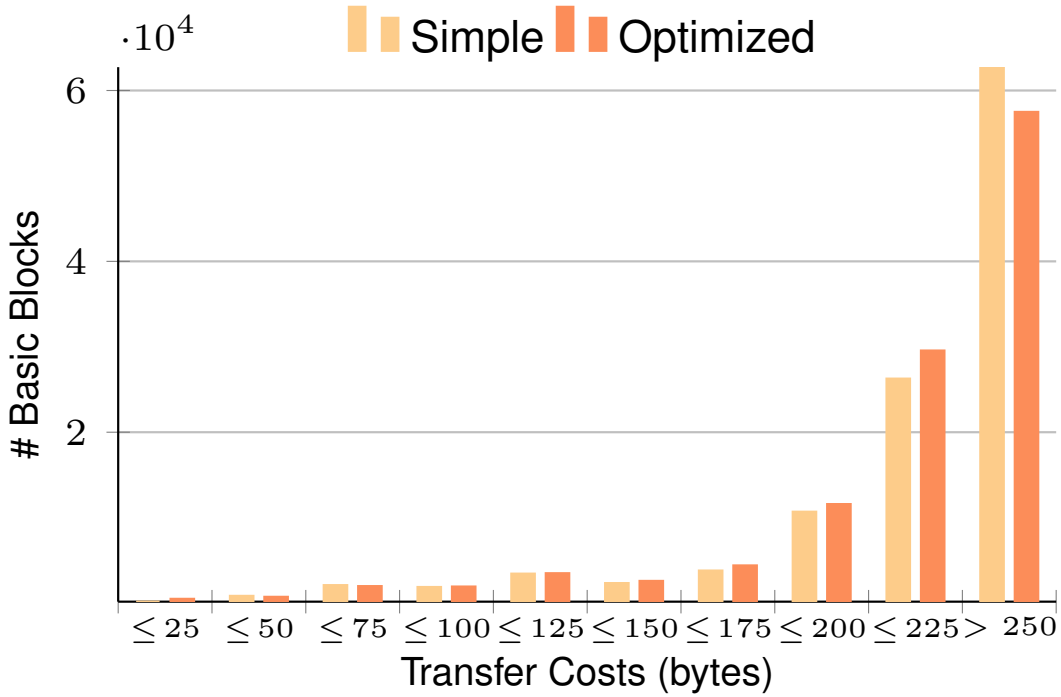
Observation

The length of the path is bounded by the stack cache size.

Experimental Setup

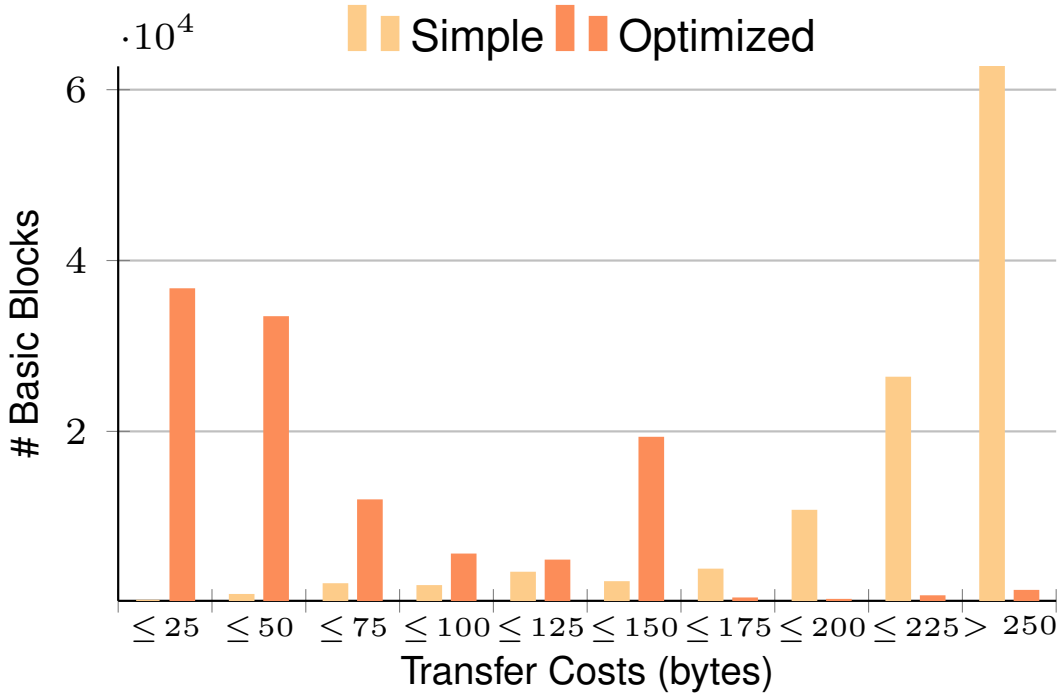
- MiBench benchmark suite
- LLVM compiler 3.5 for the Patmos processor
- Compiled with optimizations enabled (-O2)
- Stack cache configurations: 256B
- Compile benchmarks and analyze preemption costs

Experiments: Context Saving Analysis



- Improvement in around 16% of basic blocks
- Shift from right to the left

Experiments: Context Restoring Analysis



- Drastic shift from right to the left.
- Improvement in about 99% of basic blocks.
- In many cases (43.4%) no explicit memory transfer is needed.

Also in the paper...

Detailed context saving/restoring cost analyses.

- Data-flow equations controlling DP, LP, RP pointers.
- Analysis of local ensures costs.
- Analysis reserve gain.

Virtual Stack Cache: first step to integrate our analysis into schedulability analysis.

Conclusion

- We proposed a preemption cost analysis for the stack cache.
  - Context Saving Analysis.
  - Context Restoring Analysis.
- Low complexity due to function-local data-flow analyses.
- Inter-procedural effects are handled through variants of the longest path problem.
- Our analysis outperform the simple approach in most cases.

For future work:

- New task model exploiting information given by the analysis.
- Prefetching techniques to perform context saving/restoring using Virtual Stack Cache.

Thanks for your attention

Any Questions ?