HIGH PERFORMANCE STENCIL CODE GENERATION WITH LIFT

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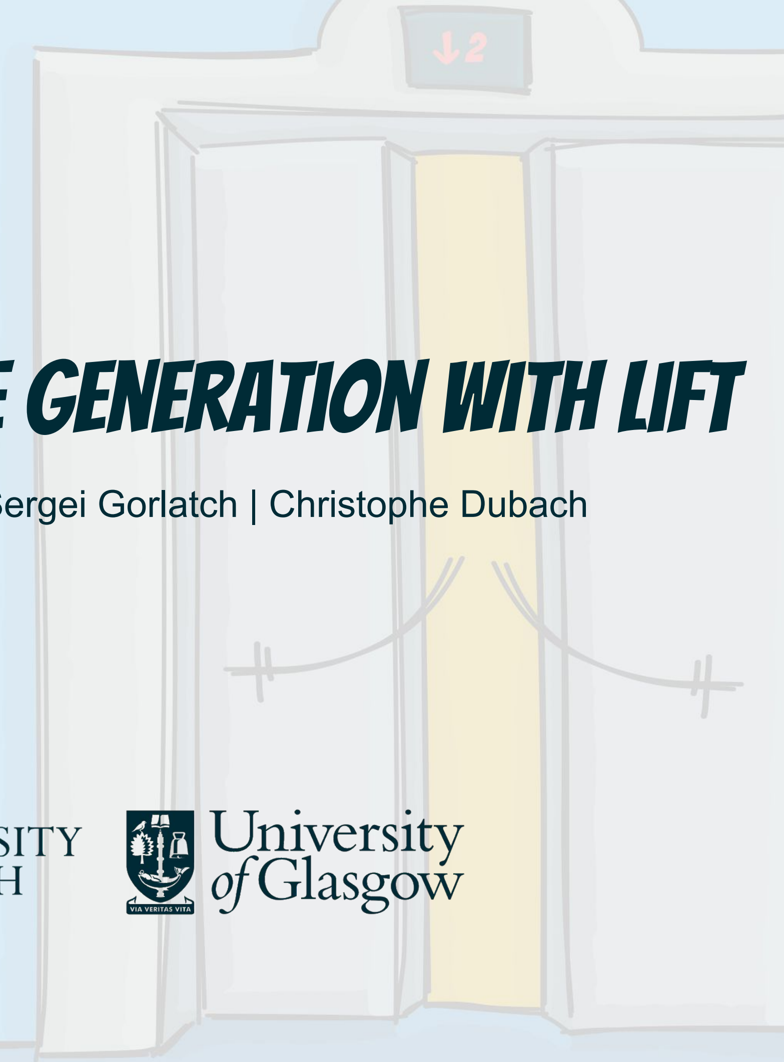
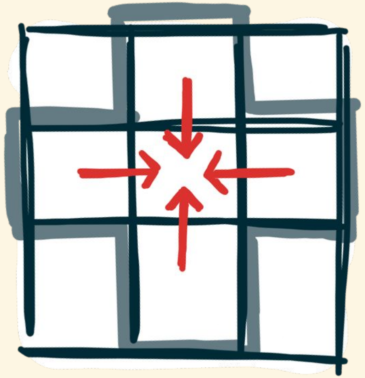
WWU MÜNSTER

THE UNIVERSITY of EDINBURGH

University of Glasgow



WHY STENCIL COMPUTATIONS?



Stencil computations are a class of kernels which update *neighboring* array elements according to a fixed pattern, called *stencil*.

Frequently occur in:

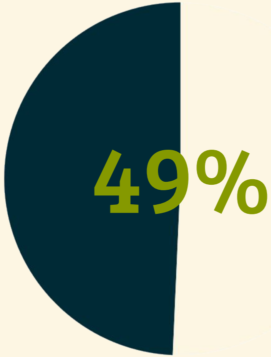
- Medical Imaging
- Physics Simulations
- Machine Learning
- PDE Solvers

WHY STENCIL COMPUTATIONS?

Stencil compute time:

HPC Center München

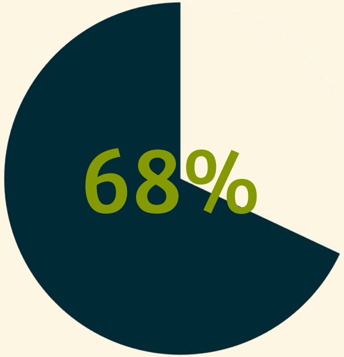
lrz



2017

HPC Center Stuttgart

HLRS



2016

Frequently occur in:

Medical Imaging

Physics Simulations

Machine Learning

PDE Solvers

YET ANOTHER STENCIL PAPER?

Cache Oblivious Stencil Computations

Effective Automatic Parallelization of Ste

Performance Modeling and Automat Optimization for Iterative Stencil Lo

3.5-D Blocking Optimization for Stencil Computations on Modern CPUs and GPUs

Auto-Generation and Auto-Tuning of GPU Clusters

Understanding the Performance of Stencil Computations on Intel's Xeon Phi

Locality Aware Concurrent Start for Stencil Applications

YASK–Yet Another Stencil Kernel: a f HPC stencil code-generation and

A Stencil Framework to Realize Large-scale Computations Beyond Devi Capacity on GPU Supercomputers

High Performance Stencil Code Generation with Lift

2005 2007 2009 2011 2013 2015 2018

ICS'05

PLDI'07

ICS'09

SC'10

CGO'12

CLUSTER'13

CGO'15

WOLFHPC'16

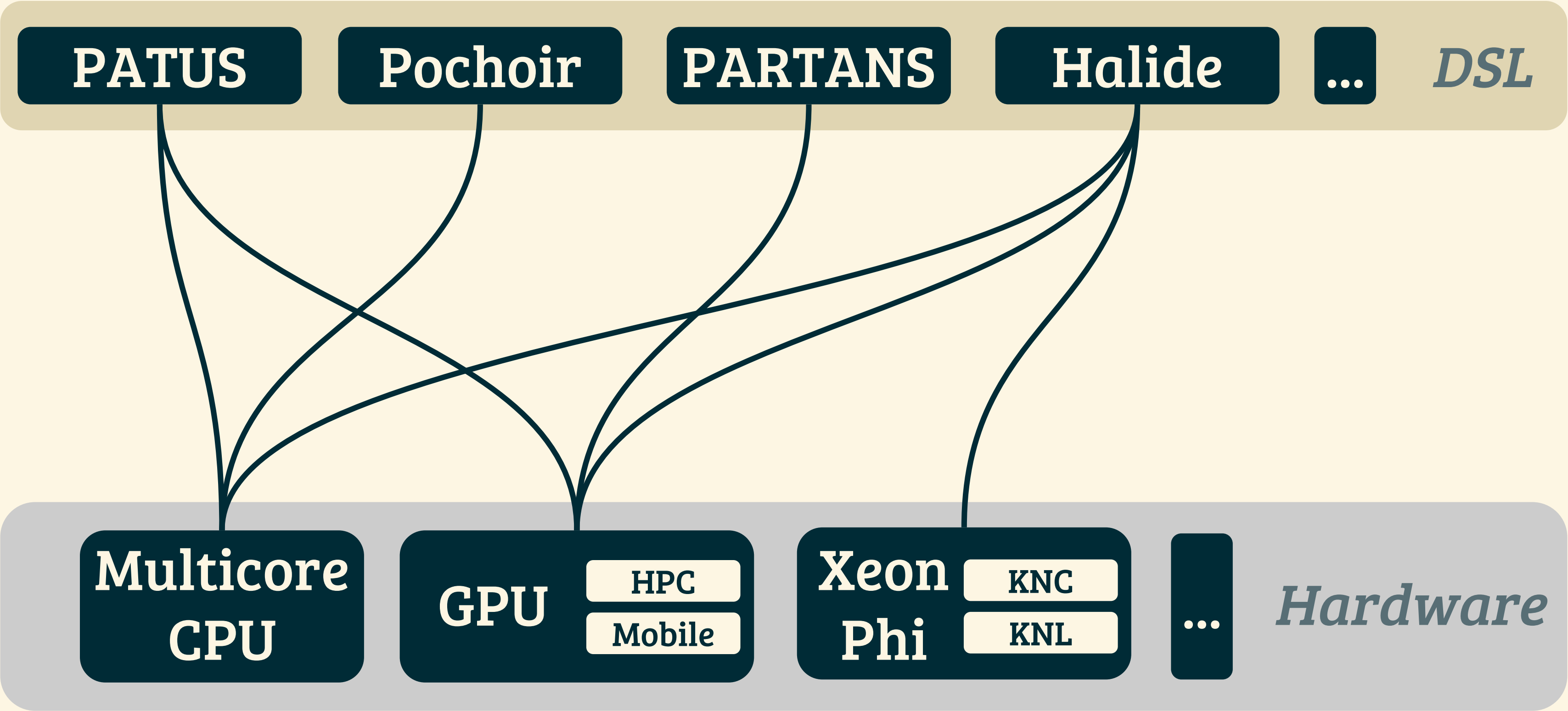
CLUSTER'17

CGO'18

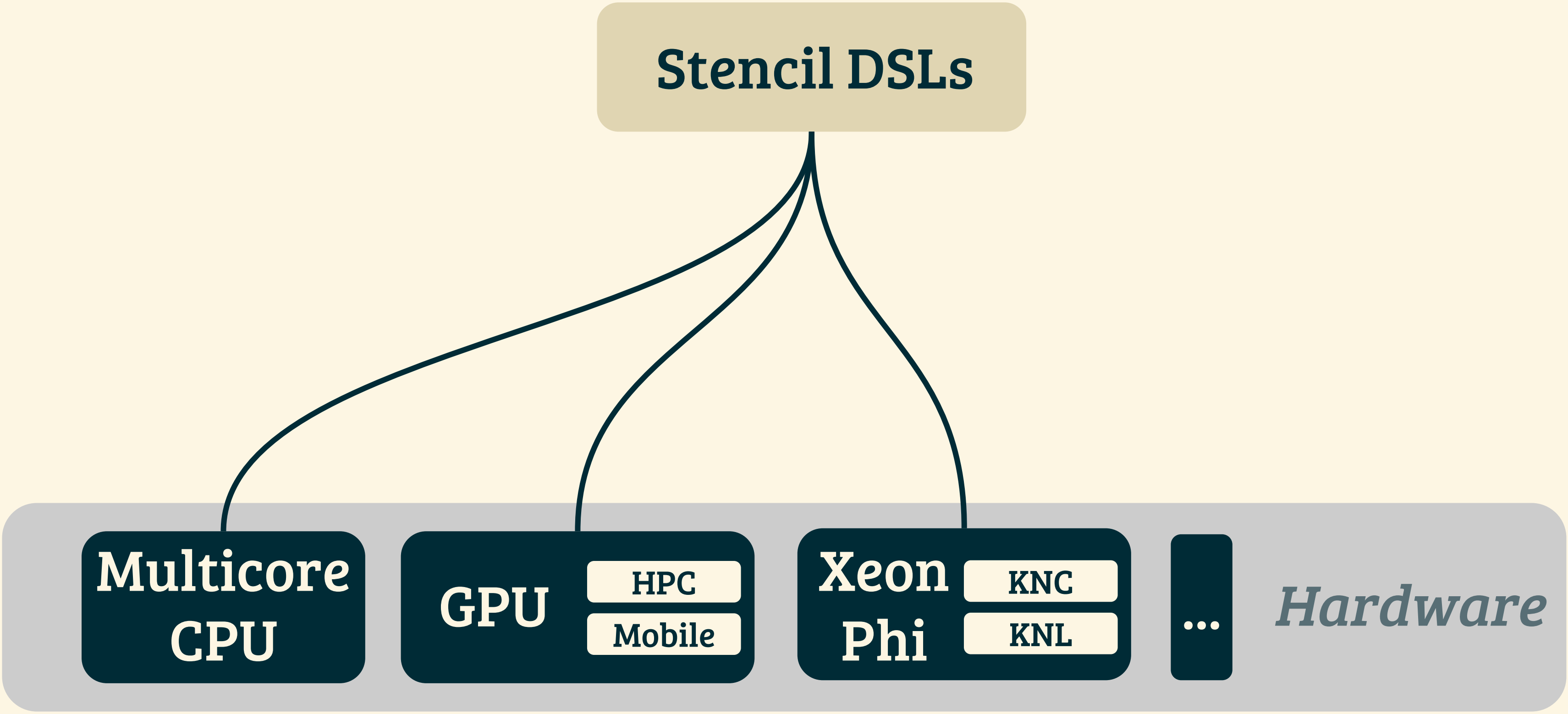
Domain Specific Languages

PATUS Pochoir PARTANS Halide ... *DSL*

Exploiting Domain Knowledge



Exploiting Domain Knowledge



Stencil DSLs

Multicore CPU

GPU

HPC

Mobile

Xeon Phi

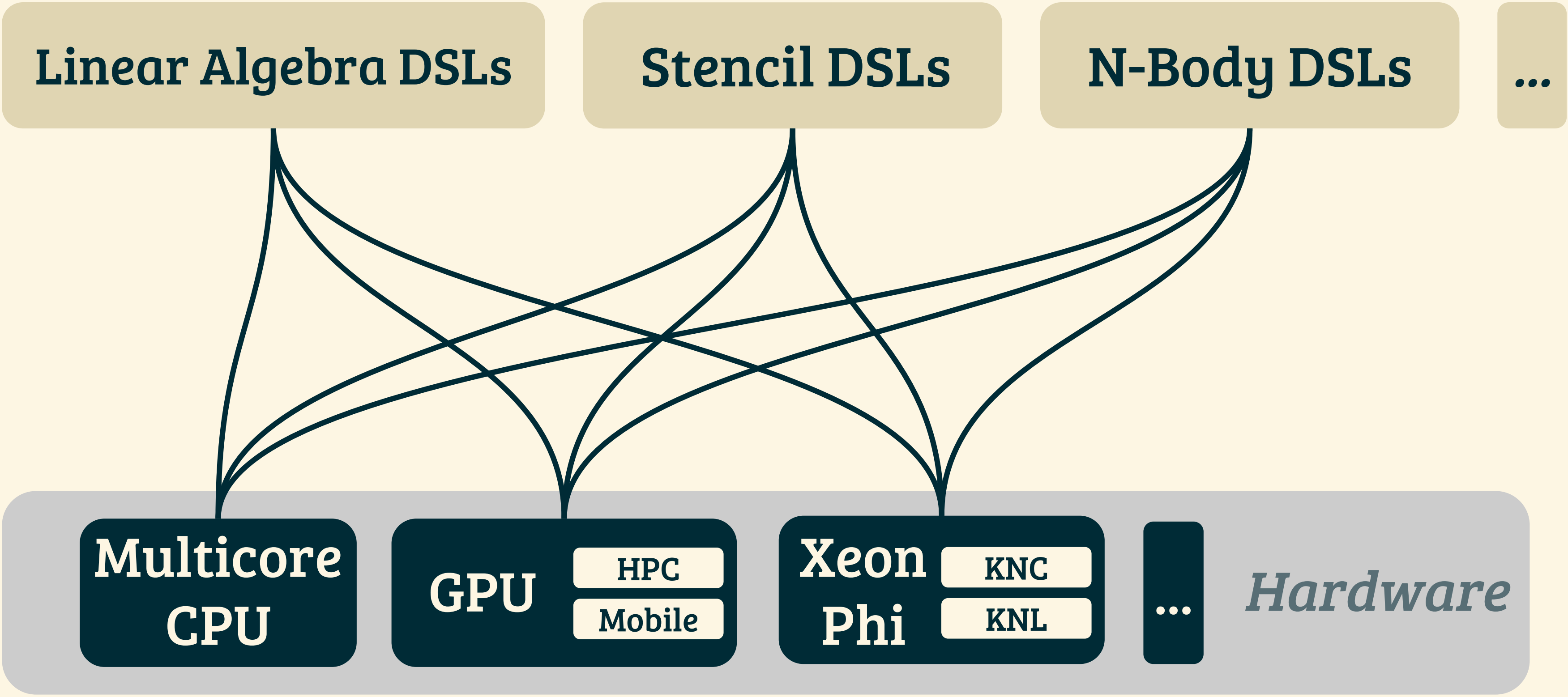
KNC

KNL

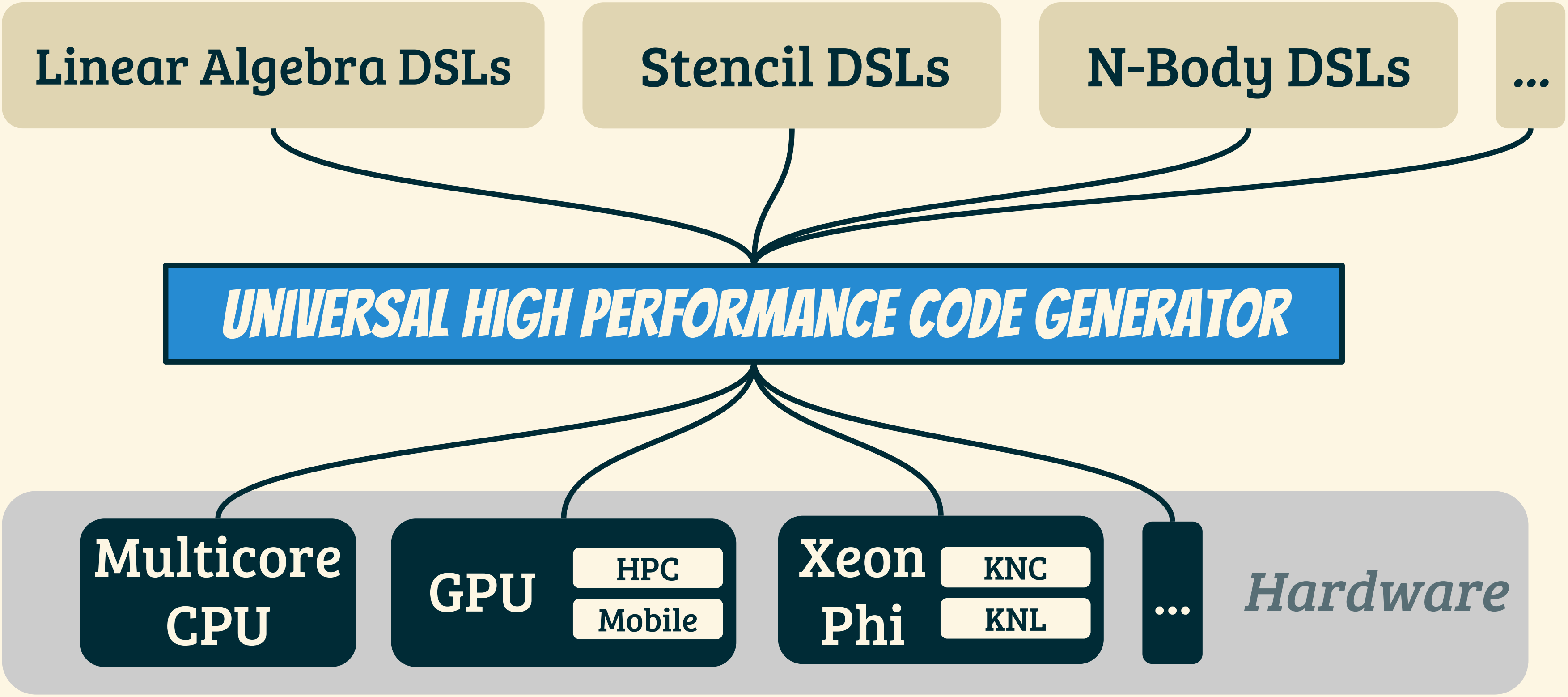
...

Hardware

Exploiting Domain Knowledge



APPROACHING PERFORMANCE PORTABILITY



Linear Algebra DSLs

Stencil DSLs

N-Body DSLs

...

UNIVERSAL HIGH PERFORMANCE CODE GENERATOR

Multicore CPU

GPU

HPC

Mobile

Xeon Phi

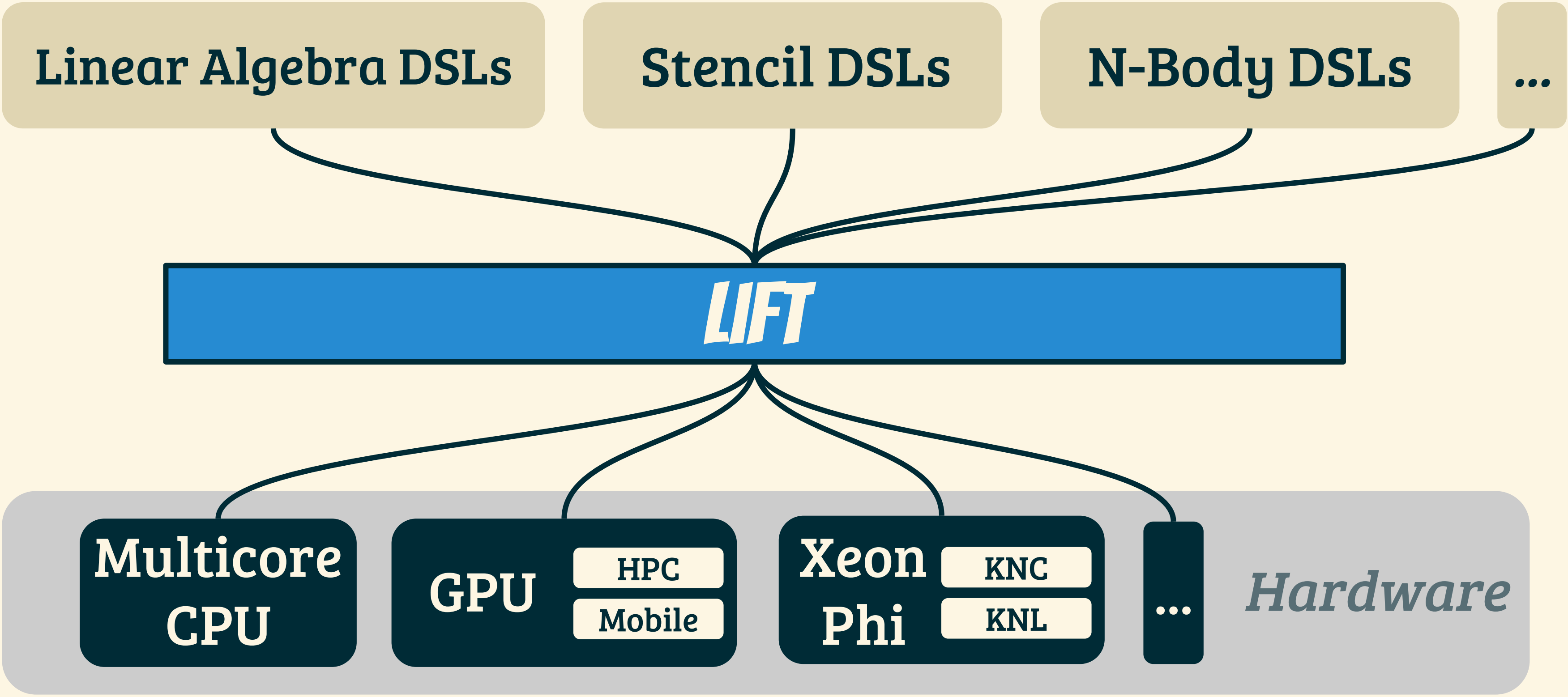
KNC

KNL

...

Hardware

APPROACHING PERFORMANCE PORTABILITY



Linear Algebra DSLs

Stencil DSLs

N-Body DSLs

...

LIFT

Multicore CPU

GPU

HPC

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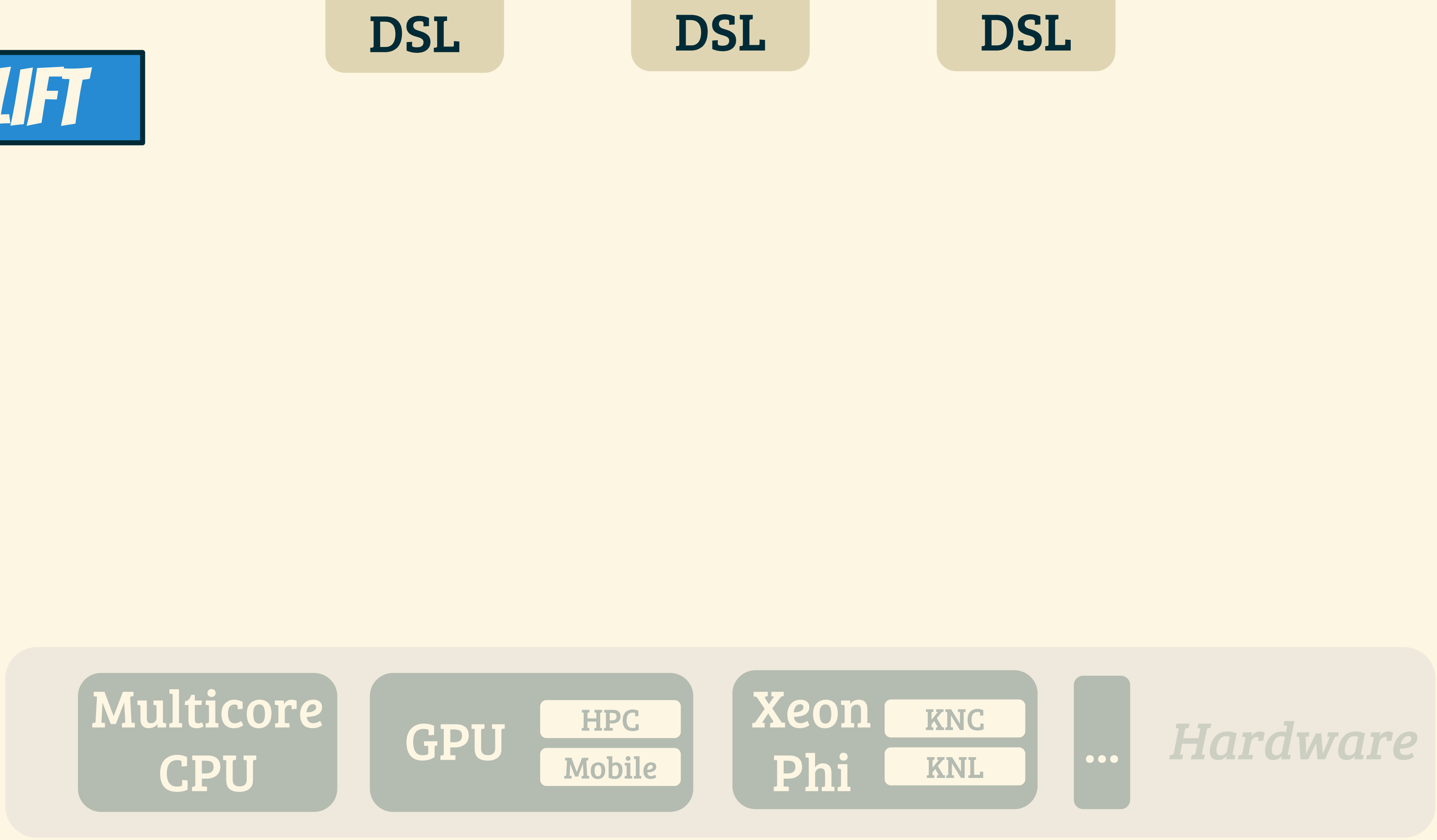
...

Hardware

LIFT



DSL

DSL

DSL

Multicore CPU

GPU

HPC

Mobile

Xeon Phi

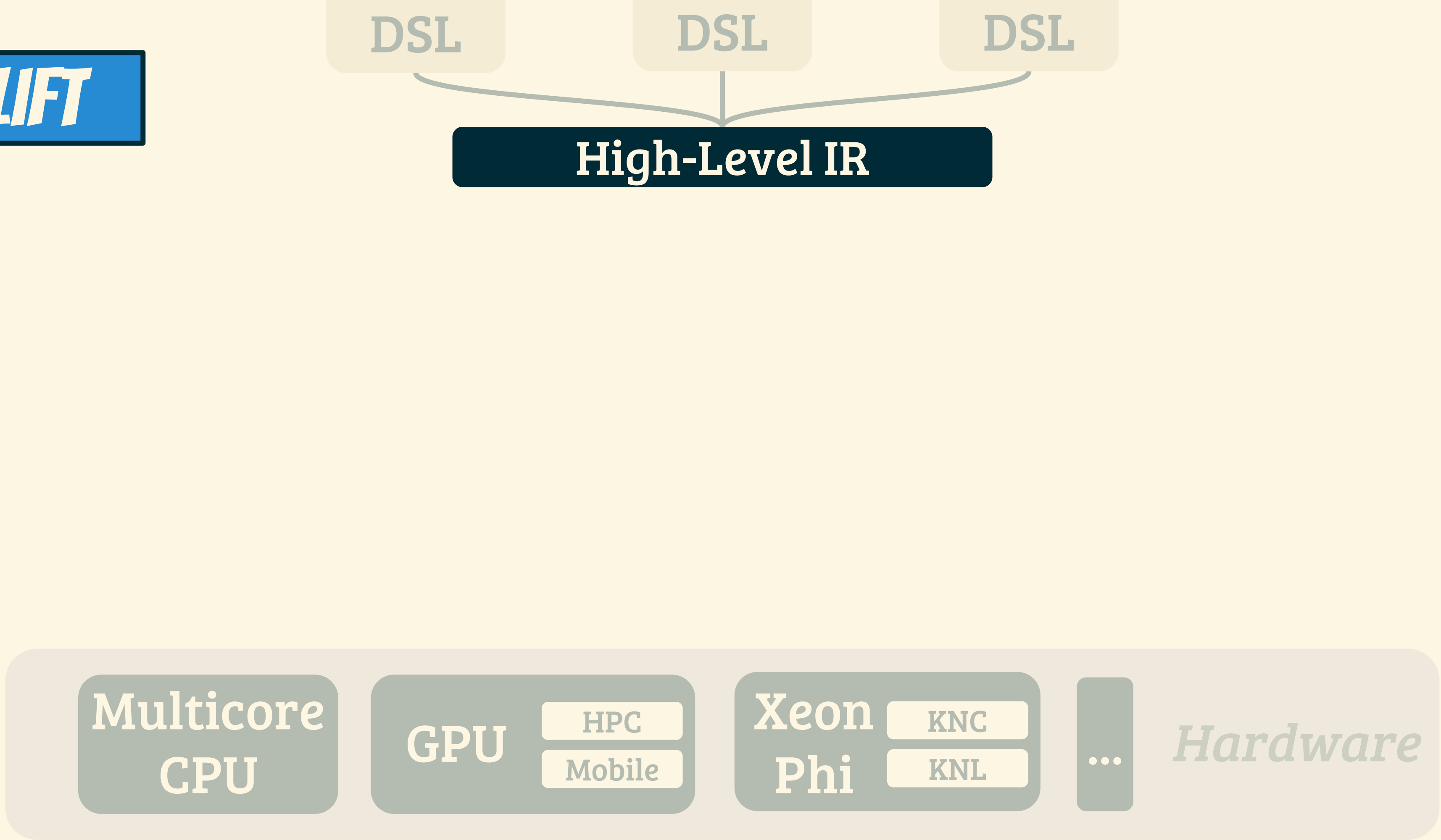
KNC

KNL

...

Hardware

LIFT



DSL

DSL

DSL

High-Level IR

Multicore CPU

GPU

HPC

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Xeon Phi

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KNL

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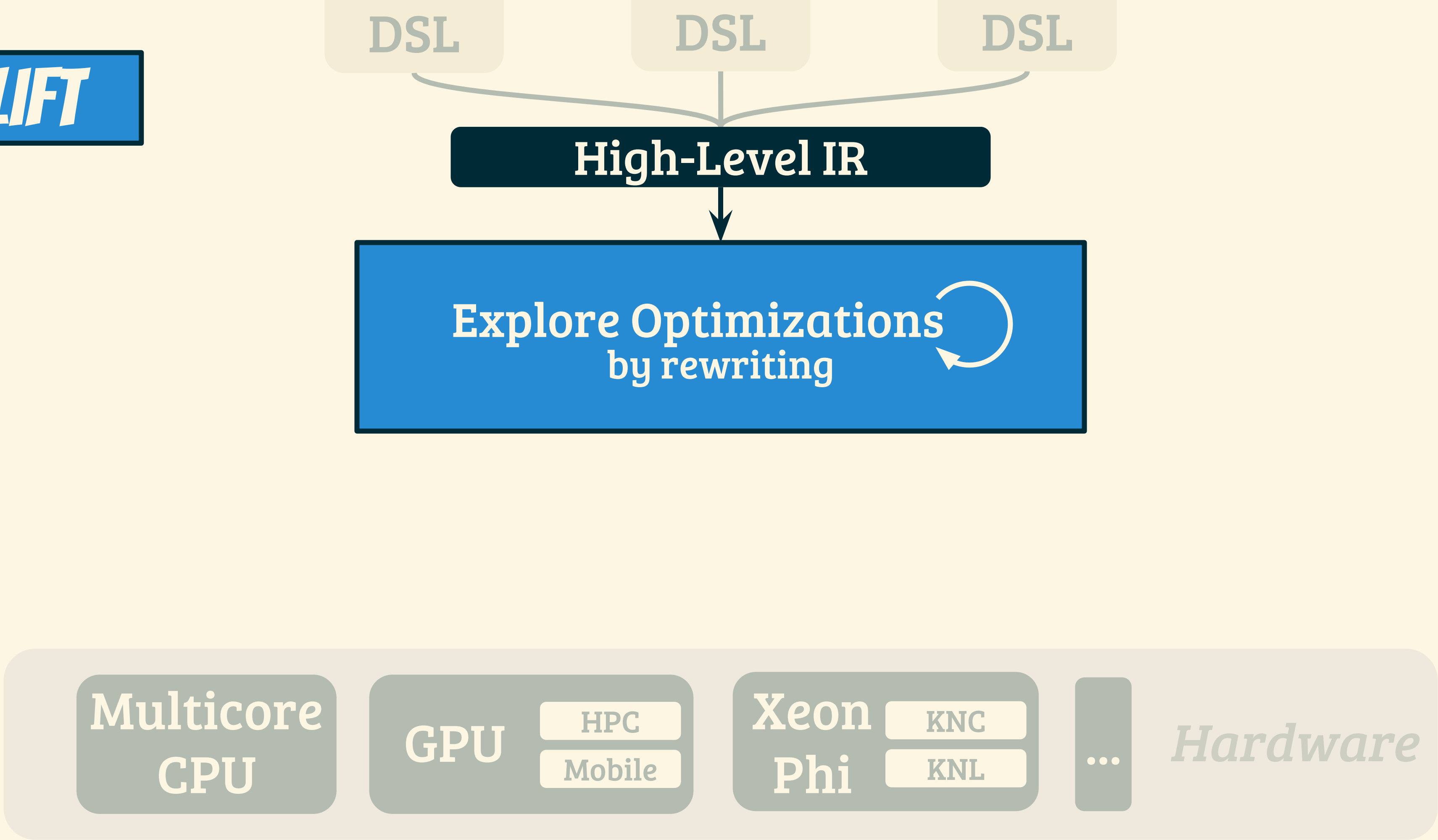
Hardware

LIFT



DSL

DSL

DSL

High-Level IR

Explore Optimizations
by rewriting

Multicore
CPU

GPU

HPC

Mobile

Xeon
Phi

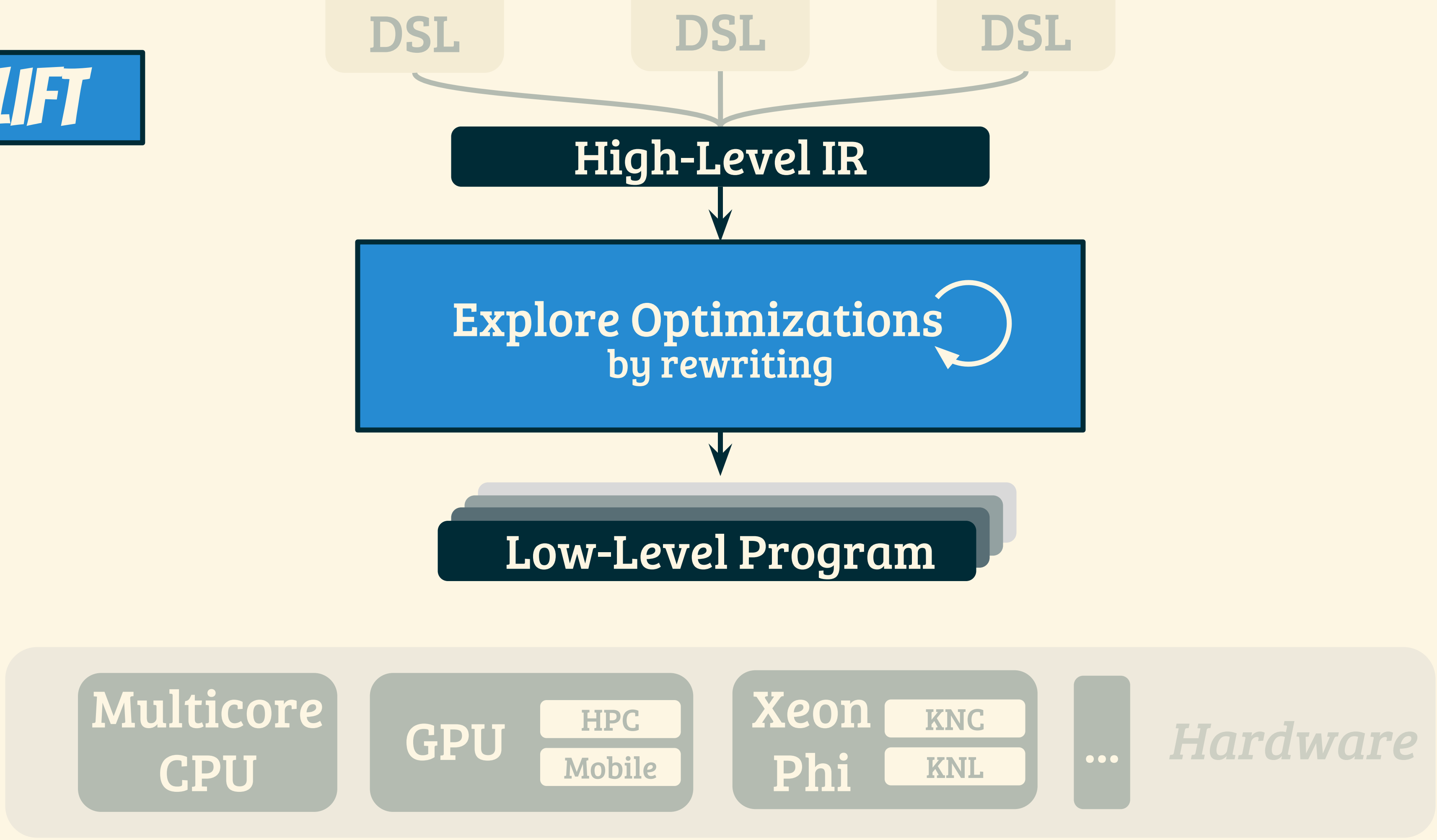
KNC

KNL

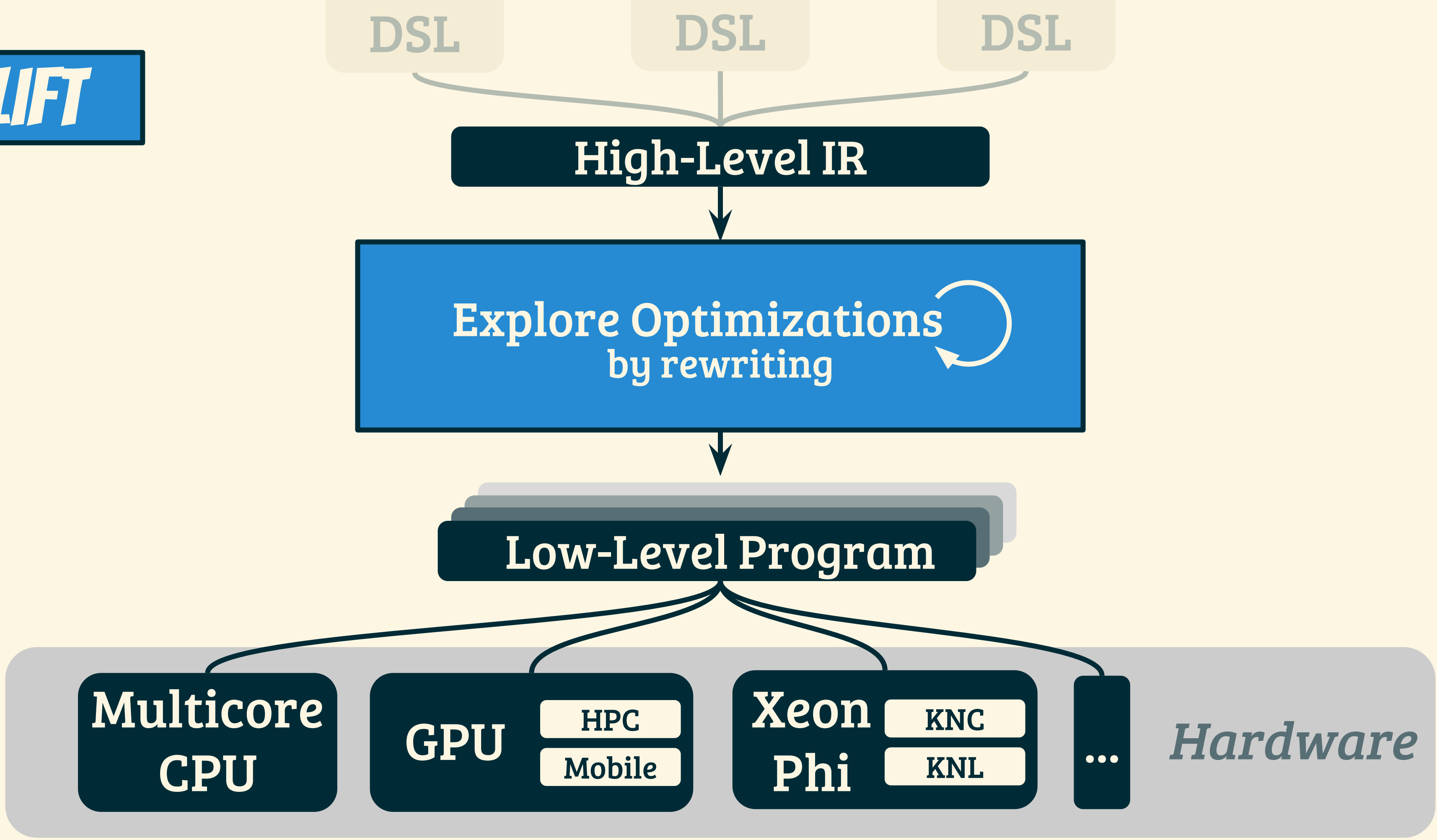
...

Hardware

LIFT


DSL
DSL
DSL
High-Level IR
Explore Optimizations
by rewriting
Low-Level Program
Multicore
CPU
GPU
HPC
Mobile
Xeon
Phi
KNC
KNL
...
Hardware

LIFT



DSL

DSL

DSL

High-Level IR

Explore Optimizations

by rewriting

Low-Level Program

Multicore CPU

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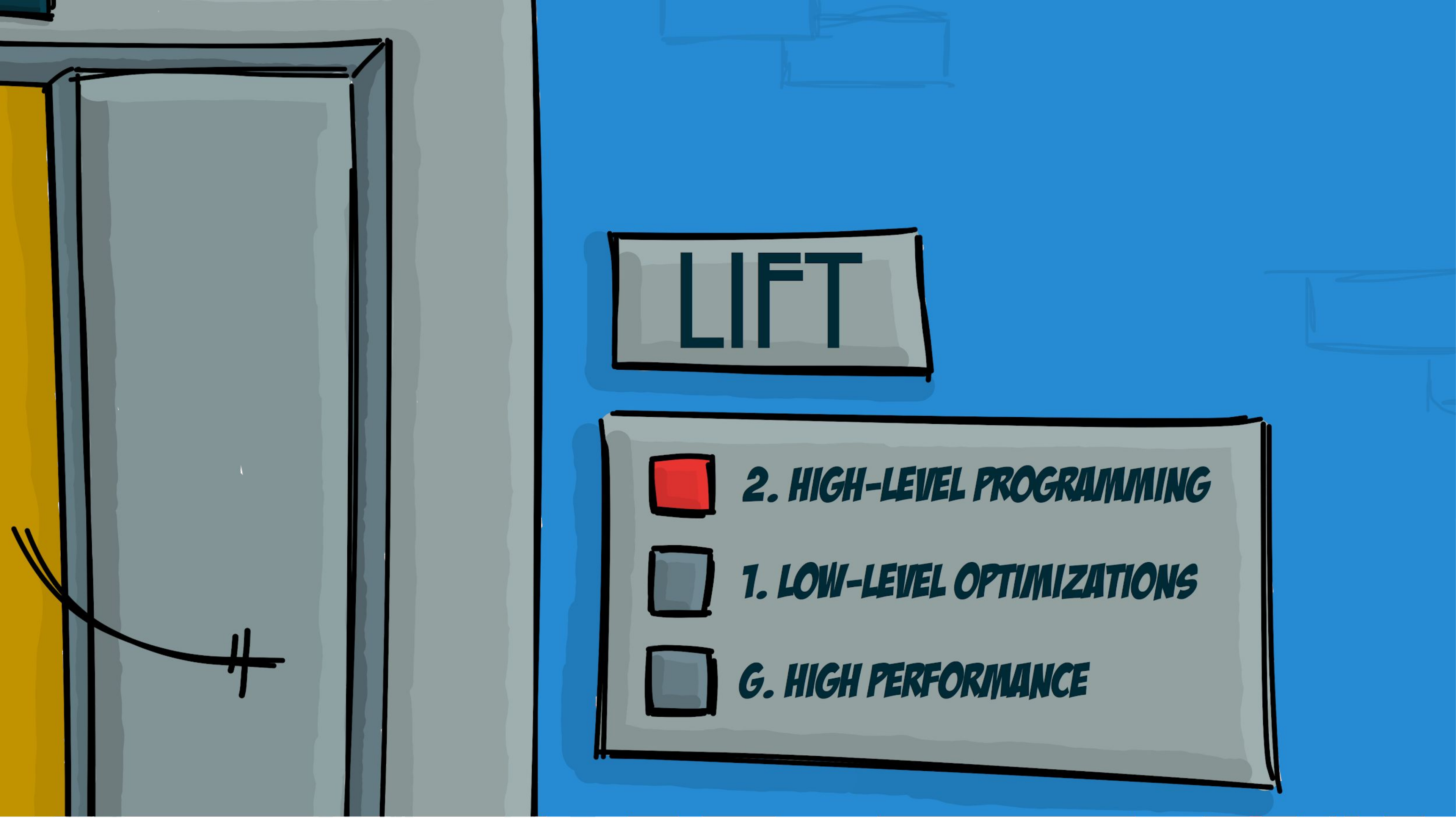
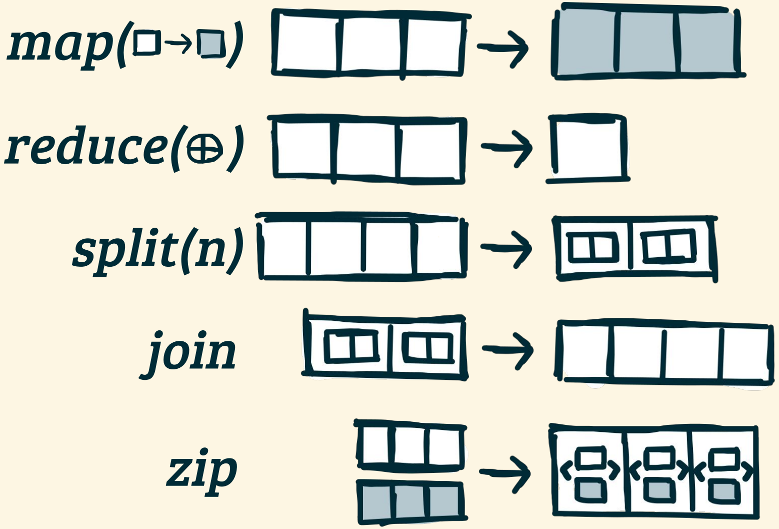
Hardware


LIFT
2. HIGH-LEVEL PROGRAMMING
1. LOW-LEVEL OPTIMIZATIONS
G. HIGH PERFORMANCE

LIFT'S HIGH-LEVEL PRIMITIVES



map(□→▨)

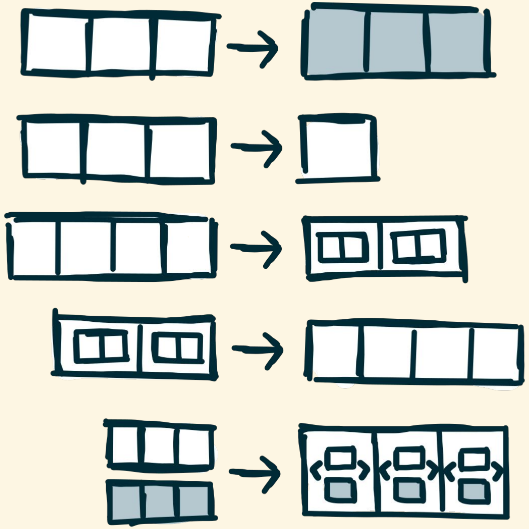
reduce(⊕)

split(n)

join

zip

LIFT'S HIGH-LEVEL PRIMITIVES



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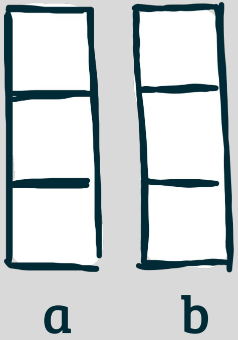
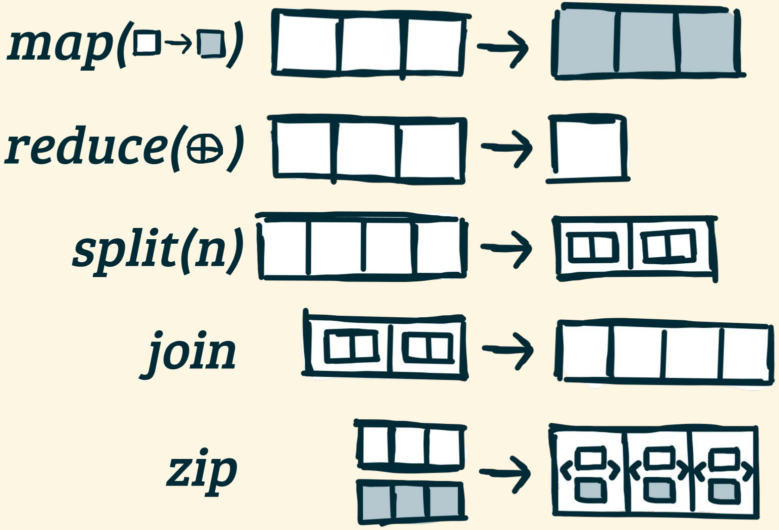
dotproduct.lift



LIFT'S HIGH-LEVEL PRIMITIVES



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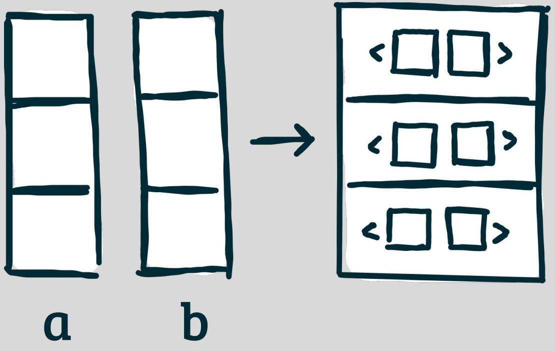
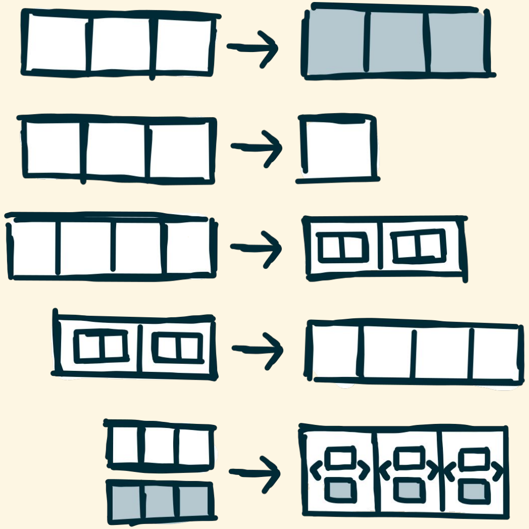


```
zip(a,b)
```

Lift's High-Level Primitives



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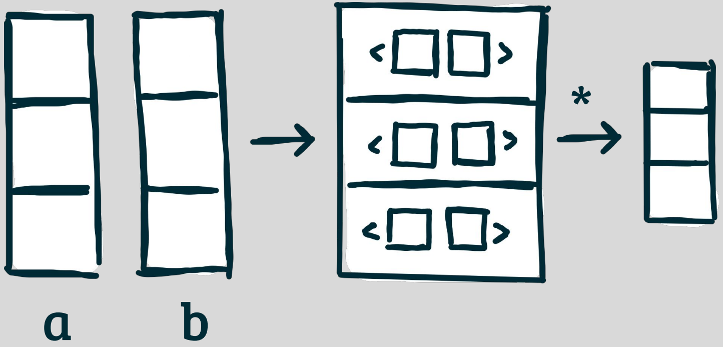
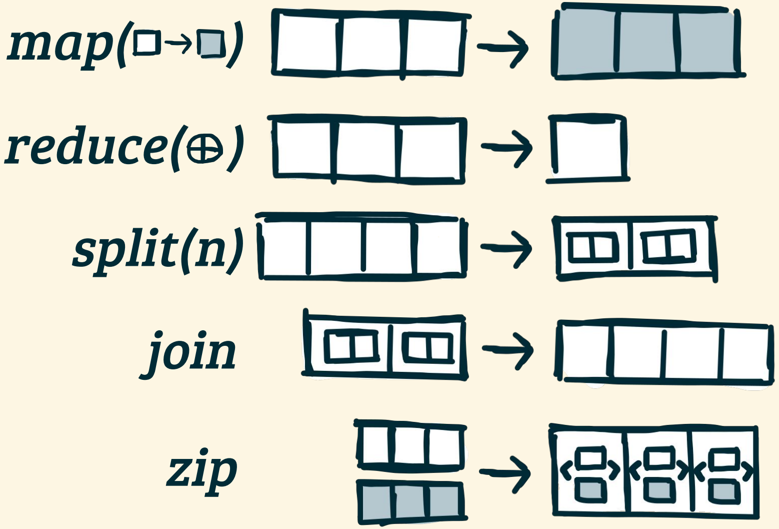


```
map(*, zip(a,b))
```

LIFT'S HIGH-LEVEL PRIMITIVES



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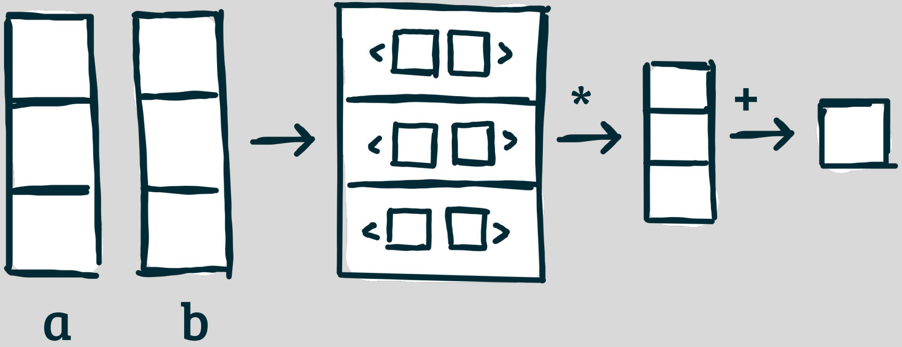
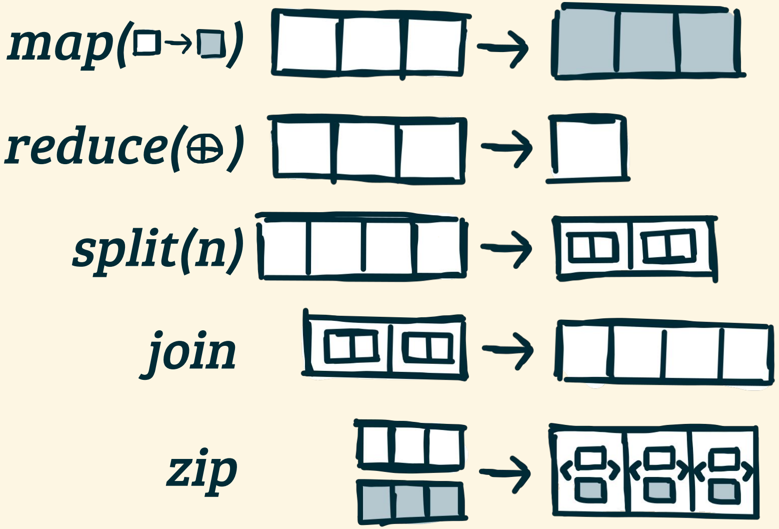


```
reduce(+,0, map(*, zip(a,b)))
```

Lift's high-level primitives



map(□→□)

reduce(⊕)

split(n)

join

zip

stencil.lift?

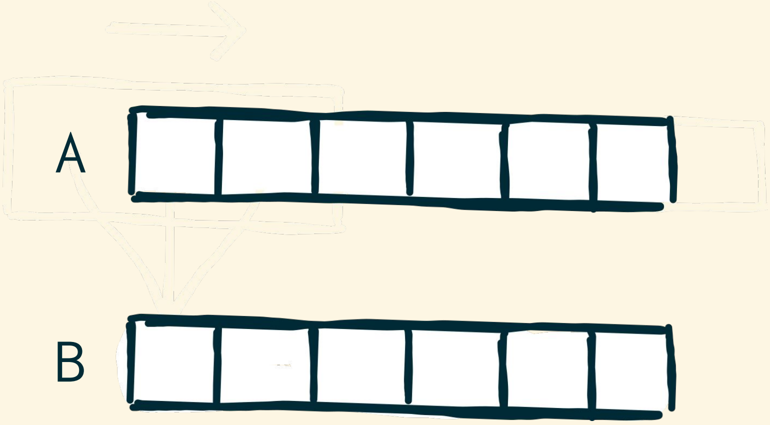
Can we express stencil computations in Lift?

Let's look at a simple stencil example...

WHAT ARE STENCIL COMPUTATIONS?

3-point-stencil.c

```
for (int i = 0; i < N ; i ++) {
    int sum = 0;
    for ( int j = -1; j <= 1; j ++) {
        int pos = i + j;
        pos = pos < 0 ? 0 : pos;
        pos = pos > N - 1 ? N - 1 : pos;
        sum += A[ pos ]; }
 B[ i ] = sum ; }
```



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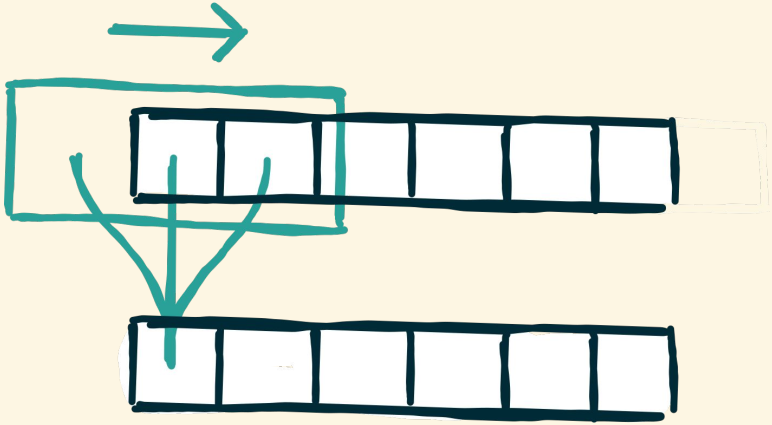

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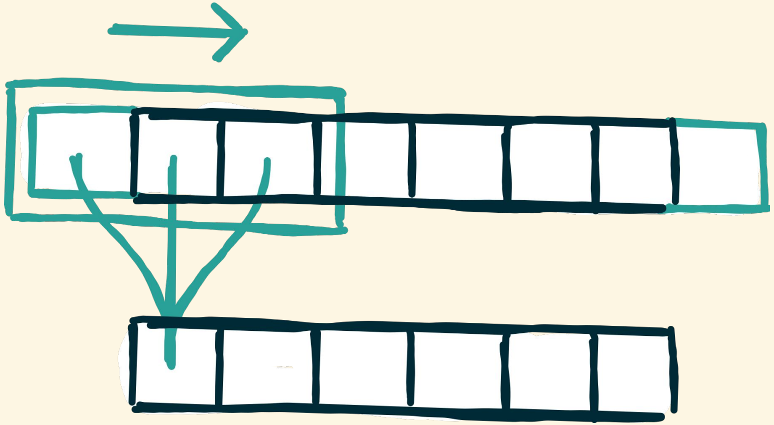
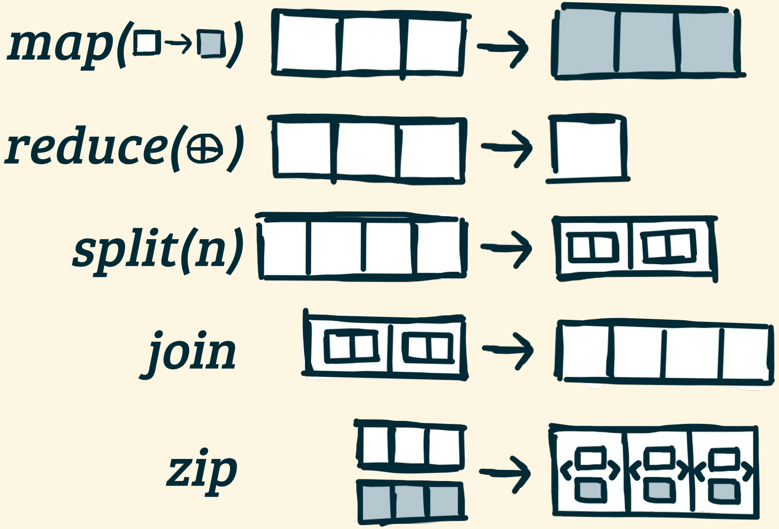


STENCIL COMPUTATIONS IN LIFT



map(□→■)

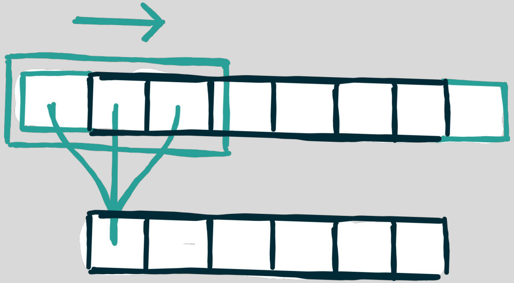
reduce(⊕)

split(n)

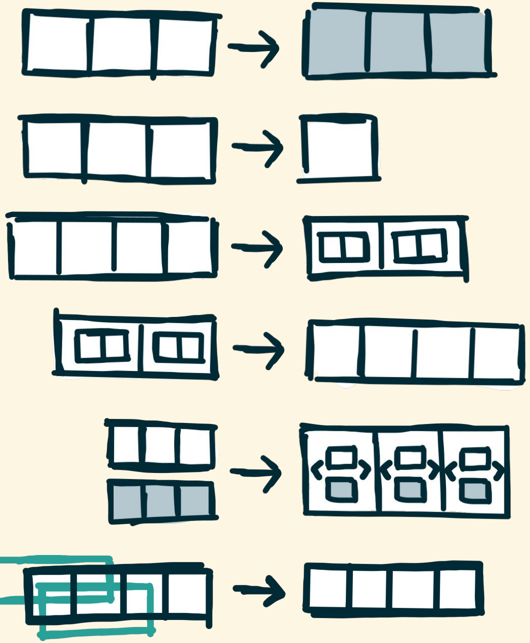
join

zip

3-point-stencil.lift



STENCIL COMPUTATIONS IN LIFT



map(□→□)

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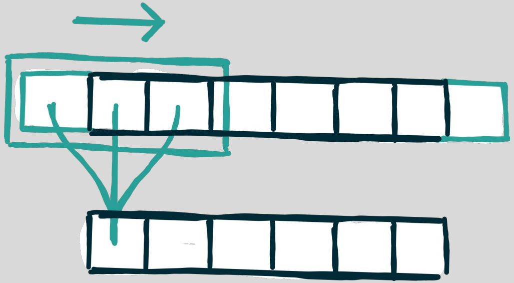
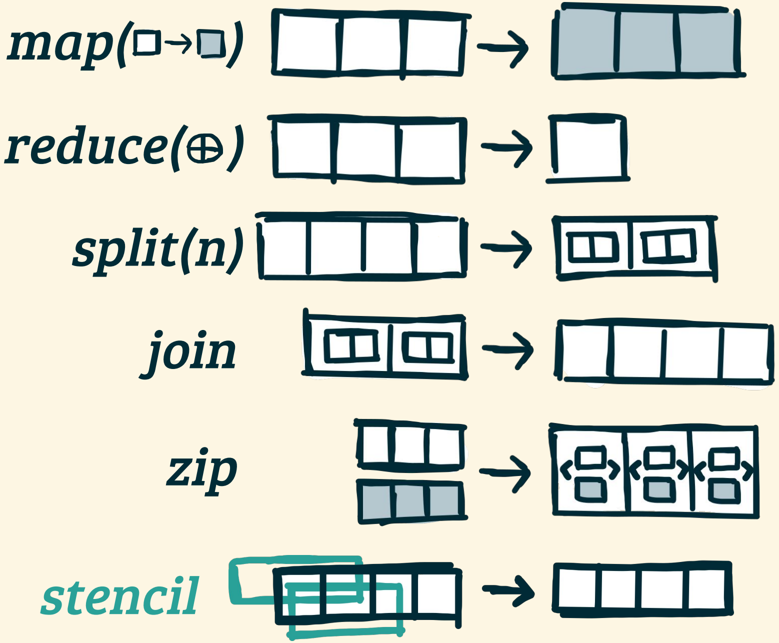
stencil

3-point-stencil.lift



Add specialized primitive: Job done?

STENCIL COMPUTATIONS IN LIFT



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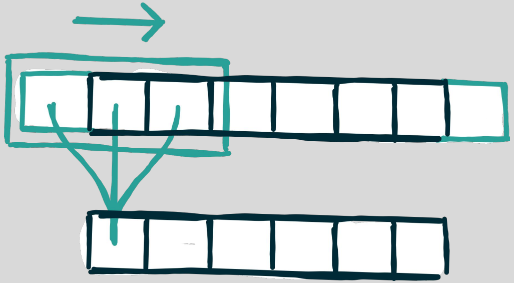
3-point-stencil.lift



Add specialized primitive: Job done?

- **No Reuse** *of existing primitives and optimizations*
- **Domain-specific** *rather than generic*
- **Multidimensional?** *is it composable?*

DECOMPOSING STENCIL COMPUTATIONS

3-point-stencil.c

```c
for (int i = 0; i < N ; i ++) {
    int sum = 0;
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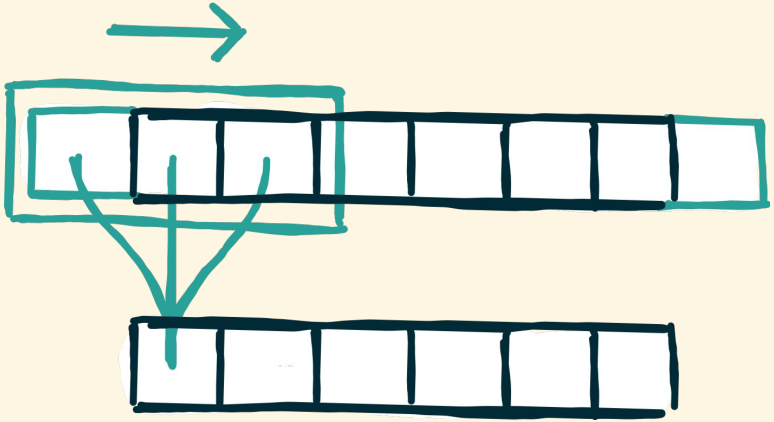
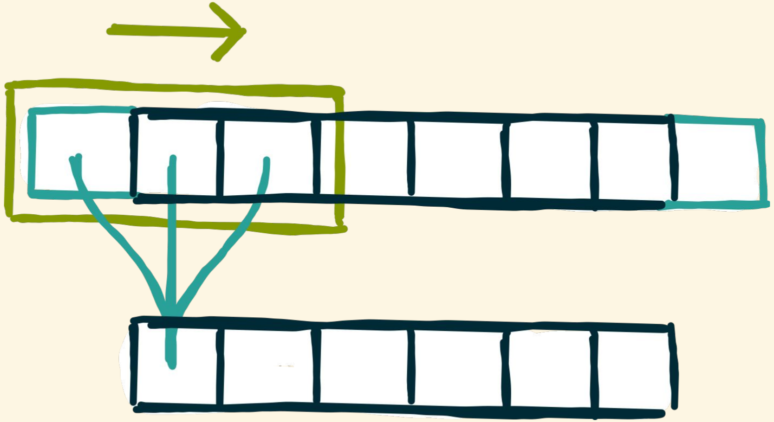


DECOMPOSING STENCIL COMPUTATIONS

3-point-stencil.c

```
for (int i = 0; i < N ; i ++) {
    int sum = 0;
    for ( int j = -1; j <= 1; j ++) {   // ( a )
        int pos = i + j;
        pos = pos < 0 ? 0 : pos;
        pos = pos > N - 1 ? N - 1 : pos;
        sum += A[ pos ]; }
 B[ i ] = sum ; }
```



(a) access neighborhoods for every element

DECOMPOSING STENCIL COMPUTATIONS

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    for ( int j = -1; j <= 1; j ++) {   // ( a )
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        pos = pos > N - 1 ? N - 1 : pos;
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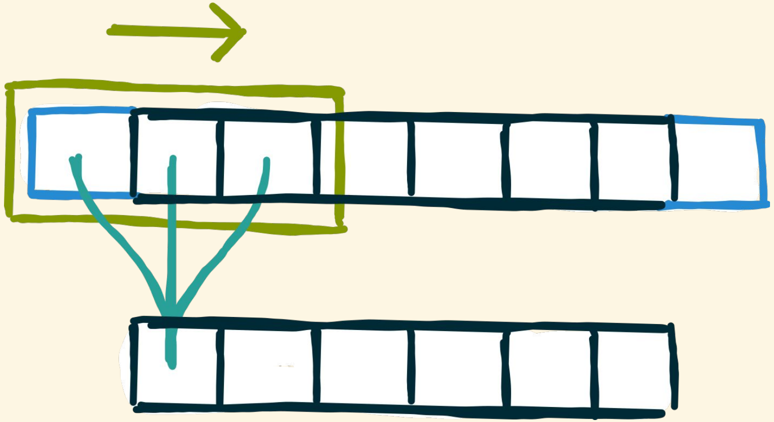
 B[ i ] = sum ; }
```



(a) access neighborhoods for every element

(b) specify boundary handling

DECOMPOSING STENCIL COMPUTATIONS

3-point-stencil.c

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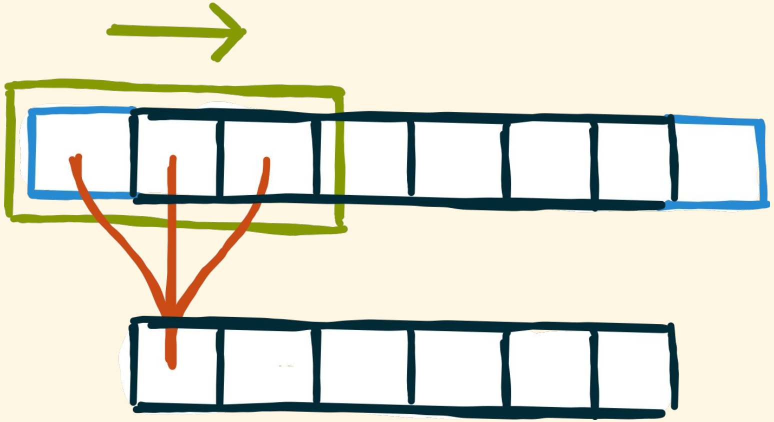
for (int i = 0; i < N ; i ++) {
    int sum = 0;
    for ( int j = -1; j <= 1; j ++) {   // ( a )
        int pos = i + j;
        pos = pos < 0 ? 0 : pos;         // ( b )
        pos = pos > N - 1 ? N - 1 : pos;
        sum += A[ pos ]; }               // ( c )
 B[ i ] = sum ; }
```



(a) access **neighborhoods** for every element

(b) specify **boundary handling**

(c) apply **stencil function** to neighborhoods

DECOMPOSING STENCIL COMPUTATIONS

3-point-stencil.c

```c
for (int i = 0; i < N ; i ++) {
    int sum = 0;
    for ( int j = -1; j <= 1; j ++) {   // ( a )
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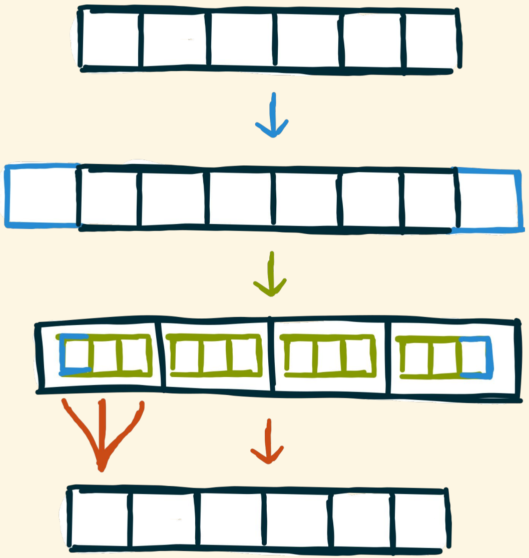
        pos = pos < 0 ? 0 : pos;        // ( b )
        pos = pos > N - 1 ? N - 1 : pos;
        sum += A[ pos ]; }              // ( c )
 B[ i ] = sum ; }
```

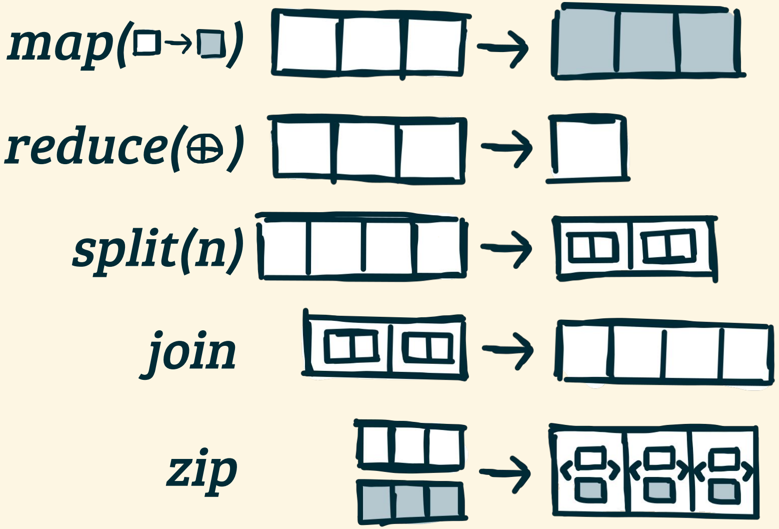


(a) access **neighborhoods** for every element

(b) specify **boundary handling**

(c) apply **stencil function** to neighborhoods

Stencil Computations in Lift



map(□→□)

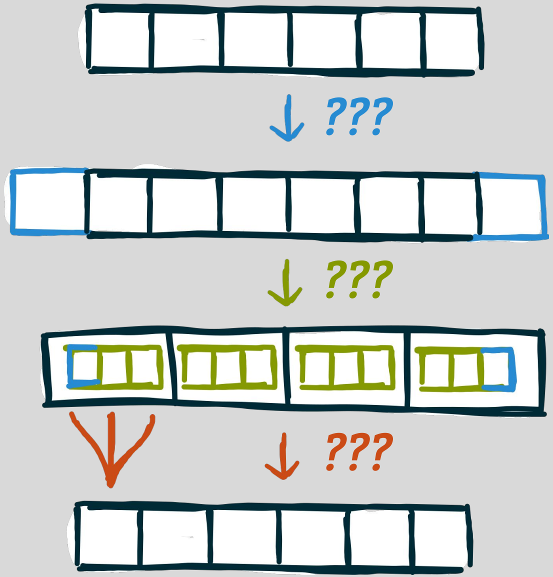
reduce(⊕)

split(n)

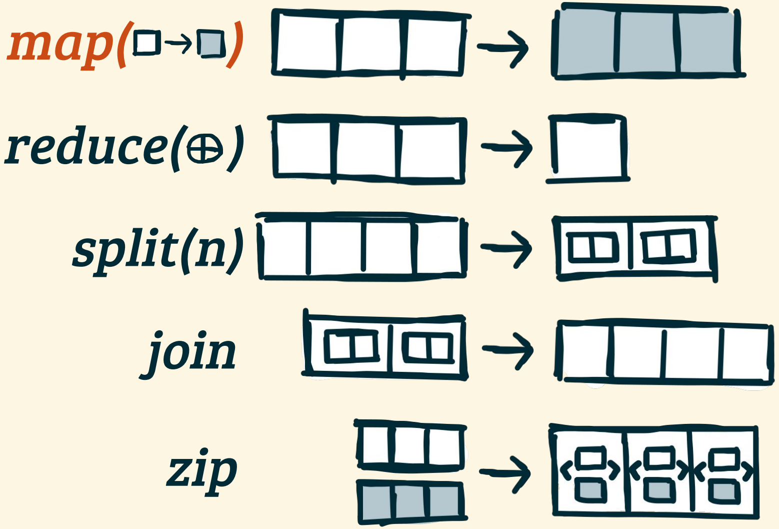
join

zip

3-point-stencil.lift



STENCIL COMPUTATIONS IN LIFT



map(□→□)

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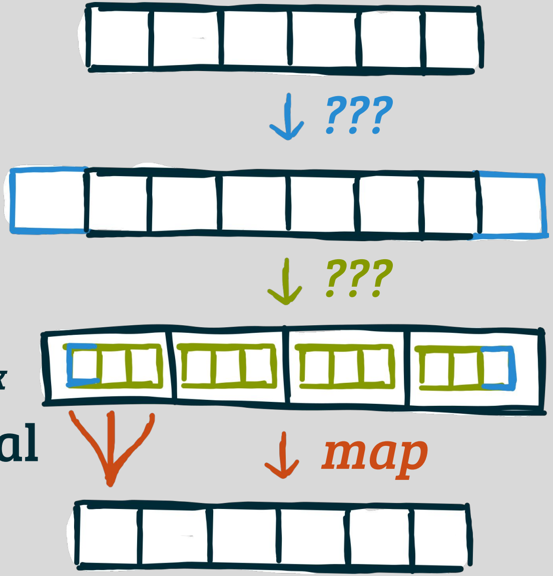
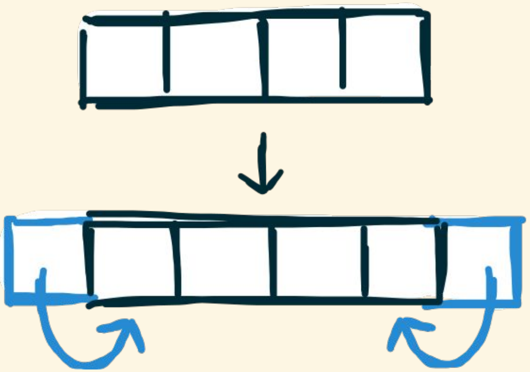
3-point-stencil.lift



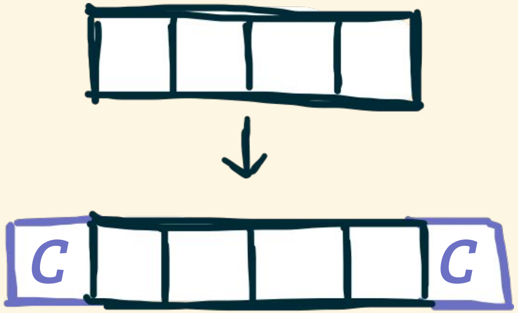
- ✓ **Reuse *map***
  allows to reuse existing rewrite rules
- ✓ **Simplicity**
  one primitive per task
- ✓ **Multidimensional**
  easily composable

BOUNDARY HANDLING USING PAD

pad (reindexing)



pad (constant)



pad-reindexing.lift

```
clamp(i, n) = (i <  0) ? 0  :
             ((i >= n) ? n-1:i)


pad(1,1,clamp, [a,b,c,d]) =
    [a,a,b,c,d,d]
```

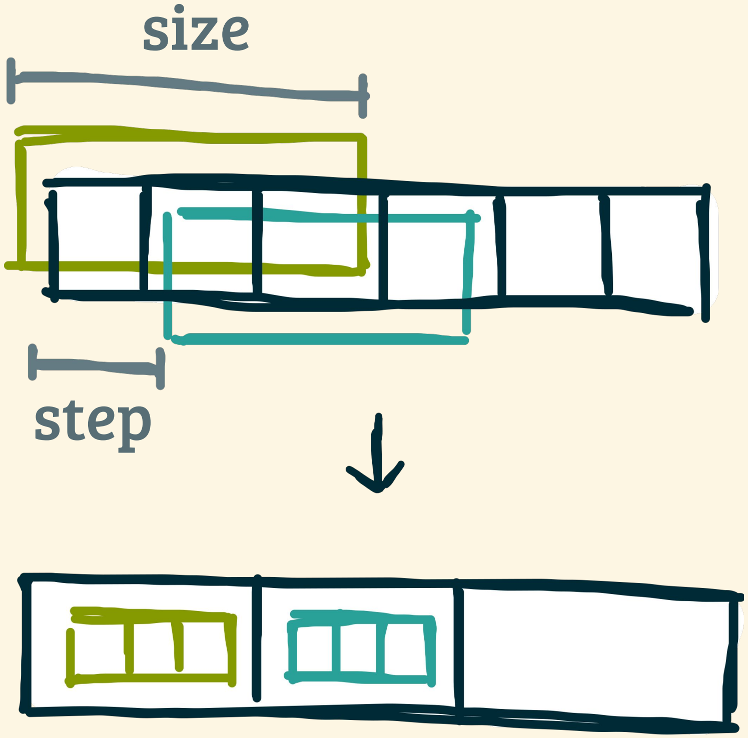
pad-constant.lift

```
constant(i, n) = C



pad(1,1,constant, [a,b,c,d]) =
    [C,a,b,c,d,C]
```

Neighborhood creation using slide

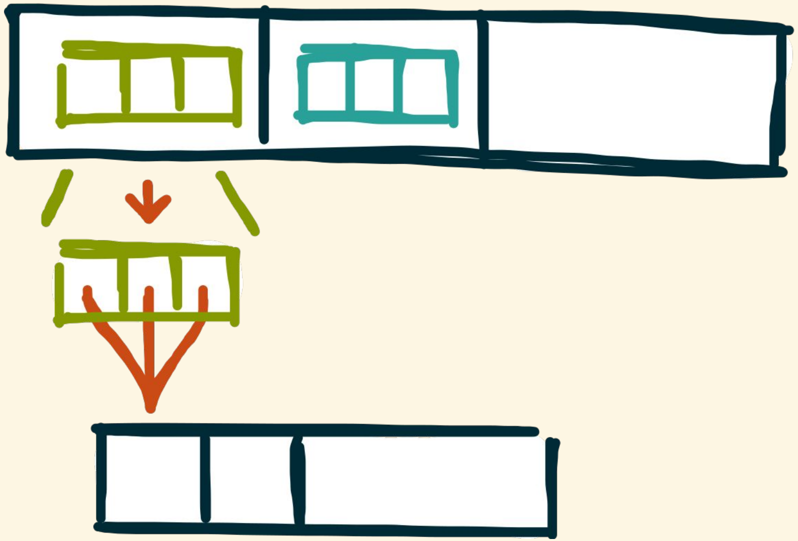


slide-example.lift

```
slide(3,1,[a,b,c,d,e]) =

    [[a,b,c],[b,c,d],[c,d,e]]
```

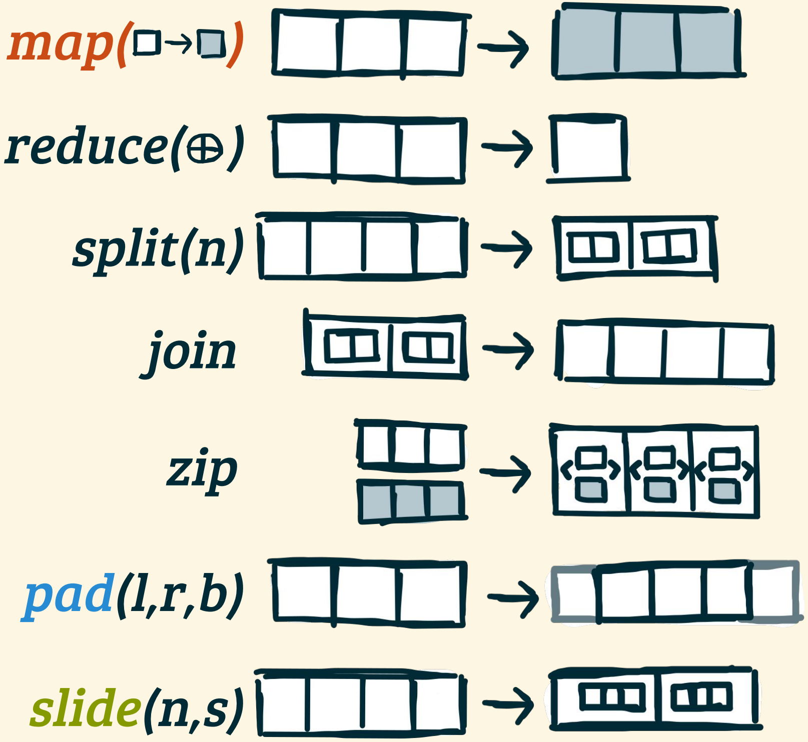
Applying stencil function using *map*



sum-neighborhoods.lift

```
map(nbh =>
  reduce(add, 0.0f, nbh))
```

Putting it together



map(□→□)

reduce(⊕)

split(n)

join

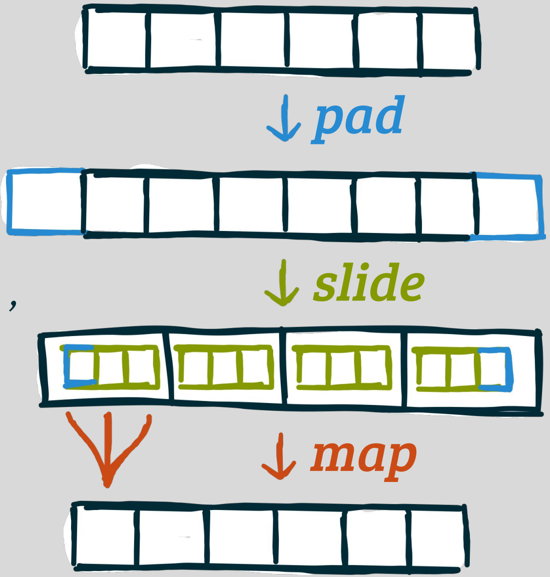
zip

pad(l,r,b)

slide(n,s)

stencil1D.lift

```
def stencil1D =
 fun(A =>
  map(reduce(add, 0.0f),
   slide(3,1,
    pad(1,1,clamp,A))))
```



↓ pad

↓ slide

↓ map

Multidimensional Stencil Computations

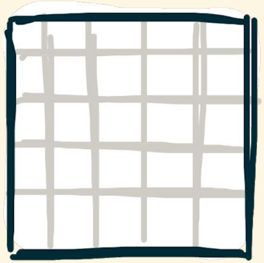
are expressed as compositions of intuitive, generic 1D primitives

Decompose to Re-Compose

MULTIDIMENSIONAL STENCIL COMPUTATIONS

are expressed as compositions of intuitive, generic 1D primitives

Decompose to Re-Compose



MULTIDIMENSIONAL STENCIL COMPUTATIONS

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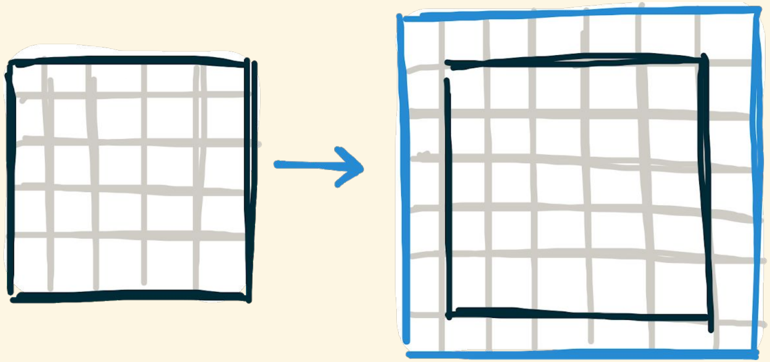
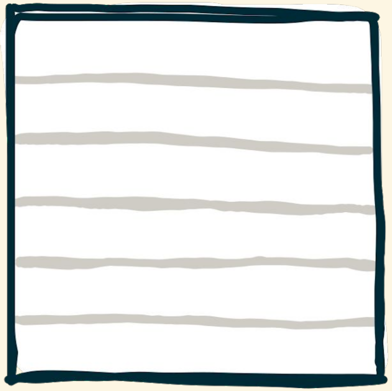


$\mathbf{pad}_2$(1,1,*clamp*,input)

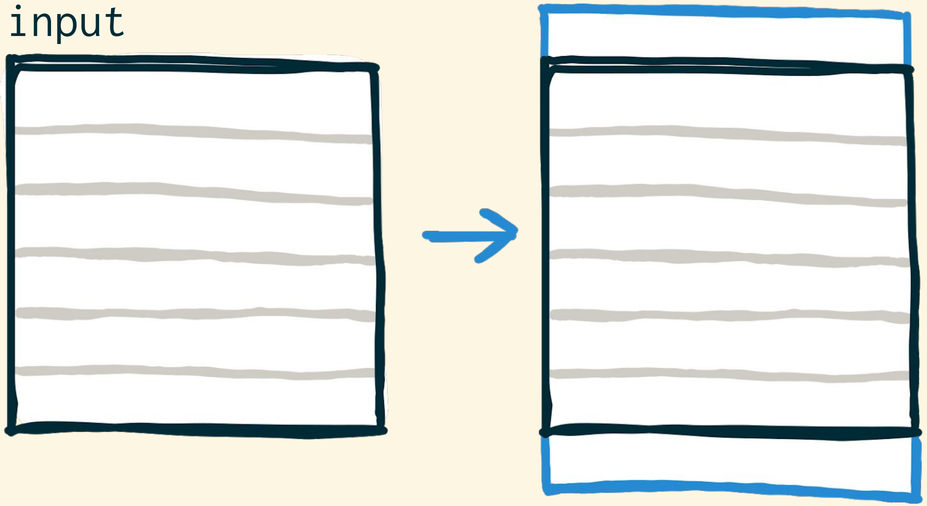
MULTIDIMENSIONAL BOUNDARY HANDLING USING PAD_2

input



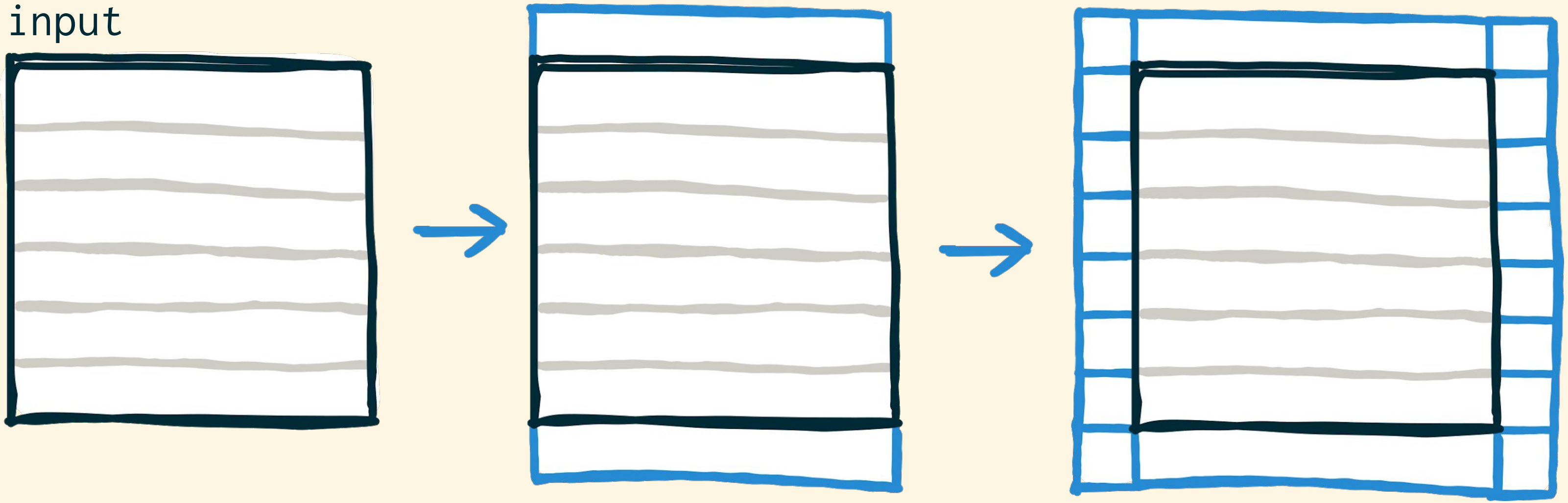
pad_2 =

Multidimensional Boundary Handling using pad_2



pad_2 = *pad*(l,r,b,input)

MULTIDIMENSIONAL BOUNDARY HANDLING USING PAD_2

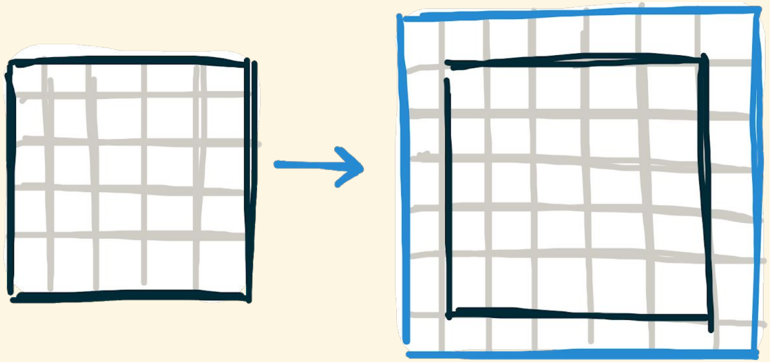


pad_2 = `map(pad(l,r,b,pad(l,r,b,input)))`

MULTIDIMENSIONAL STENCIL COMPUTATIONS

are expressed as compositions of intuitive, generic 1D primitives

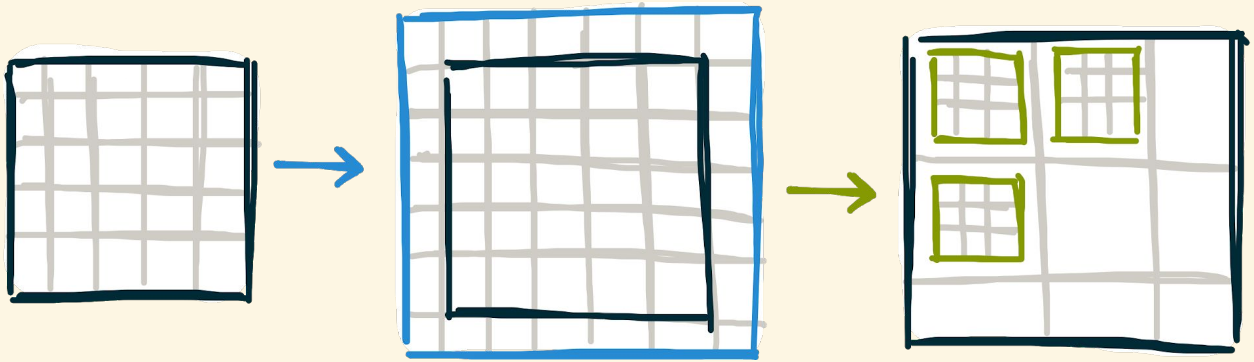
Decompose to Re-Compose



pad$_2$(1,1,*clamp*,input)

MULTIDIMENSIONAL STENCIL COMPUTATIONS

are expressed as compositions of intuitive, generic 1D primitives

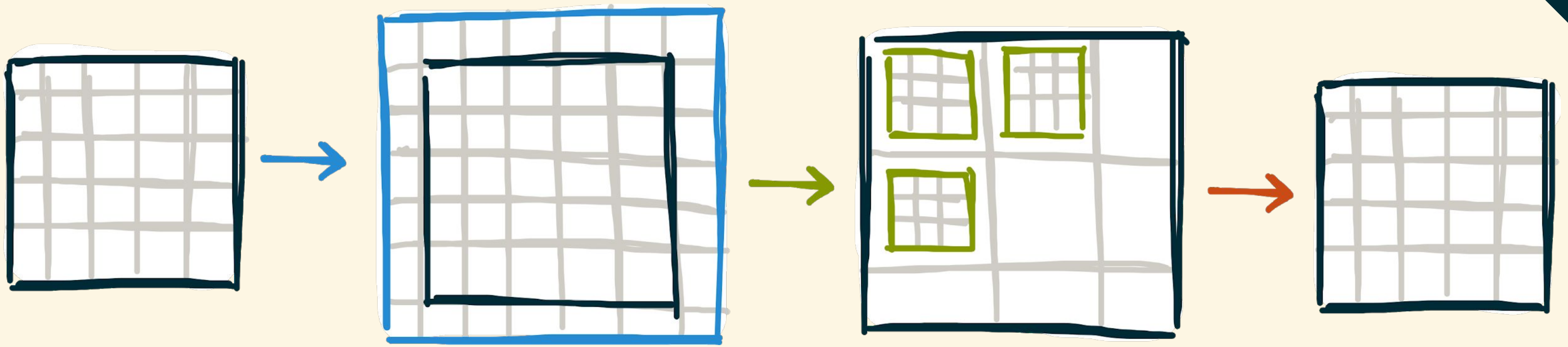


$\mathit{slide}_2(3,1,\ \mathit{pad}_2(1,1,\mathit{clamp},\mathtt{input}))$

Decompose to Re-Compose

Multidimensional Stencil Computations

are expressed as compositions of intuitive, generic 1D primitives

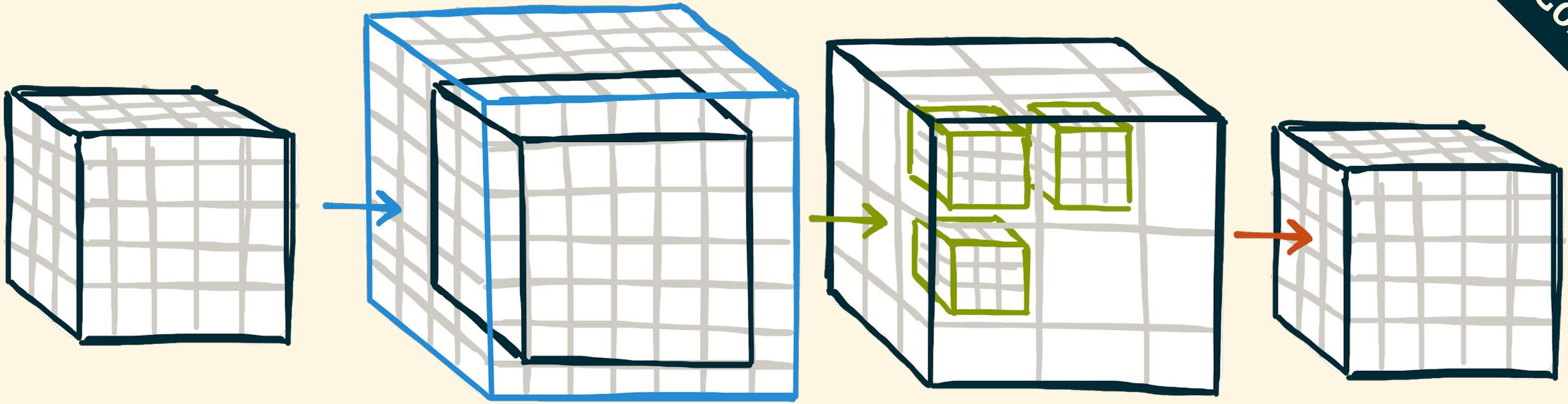


$$\mathtt{map}_2(\mathit{sum},\ \mathtt{slide}_2(3,1,\ \mathtt{pad}_2(1,1,\mathit{clamp},\mathtt{input})))$$

MULTIDIMENSIONAL STENCIL COMPUTATIONS

are expressed as compositions of intuitive, generic 1D primitives

Decompose to Re-Compose

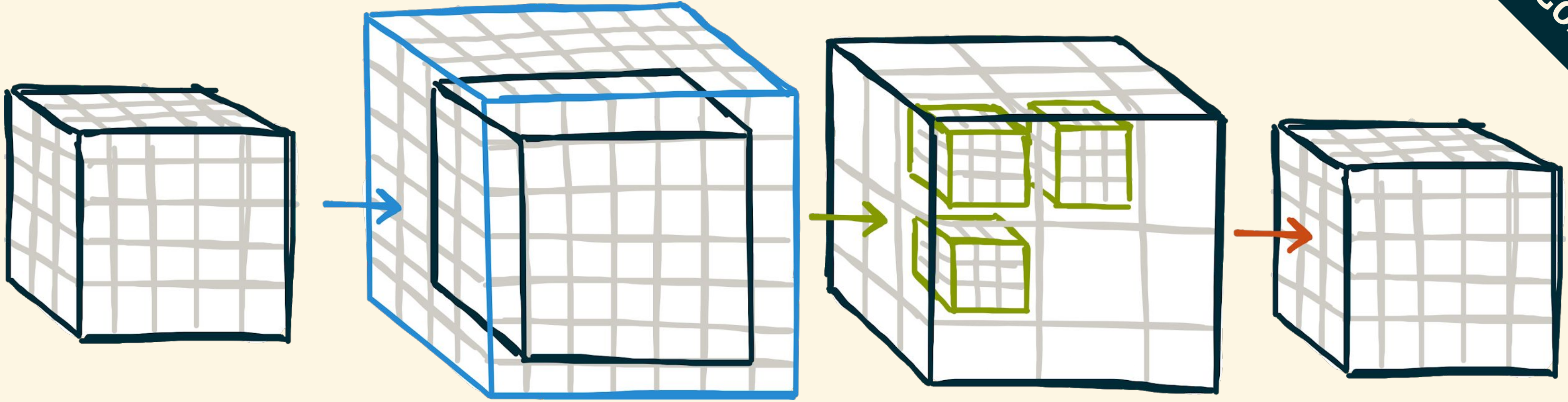


$map_3(sum,\ slide_3(3,1,\ pad_3(1,1,clamp,\text{input})))$

MULTIDIMENSIONAL STENCIL COMPUTATIONS

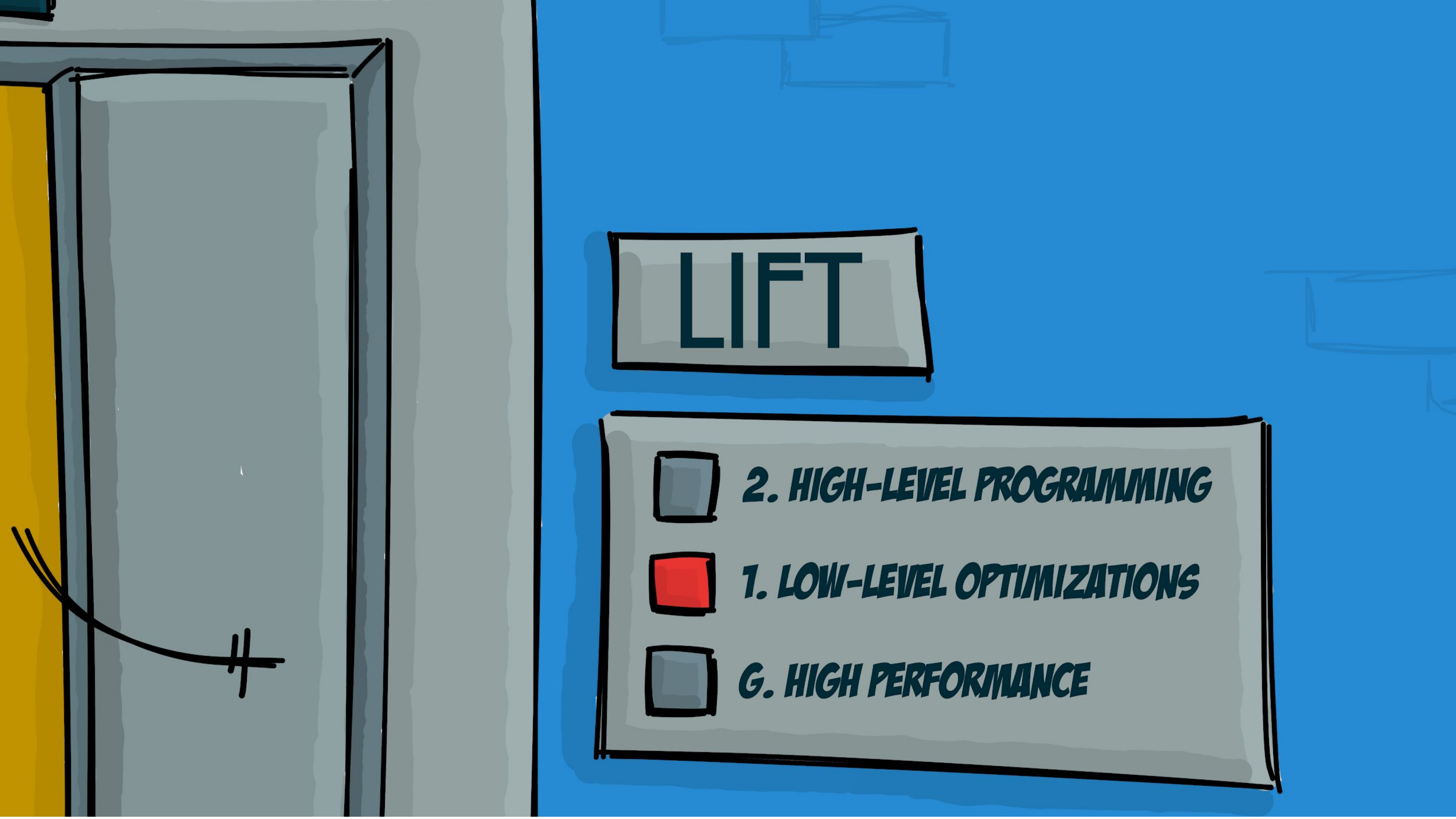
are expressed as compositions of intuitive, generic 1D primitives

Decompose to Re-Compose



$map_3(sum,\ slide_3(3,1,\ pad_3(1,1,clamp,\mathrm{input})))$

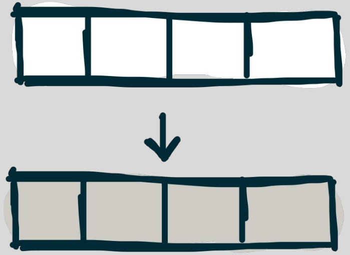
Advantages: ✓ Compact Language ✓ Reuse Rewrites ✓ Simple Compilation


LIFT
2. HIGH-LEVEL PROGRAMMING
1. LOW-LEVEL OPTIMIZATIONS
G. HIGH PERFORMANCE

Reusing Existing Rewrite Rules

Divide & Conquer

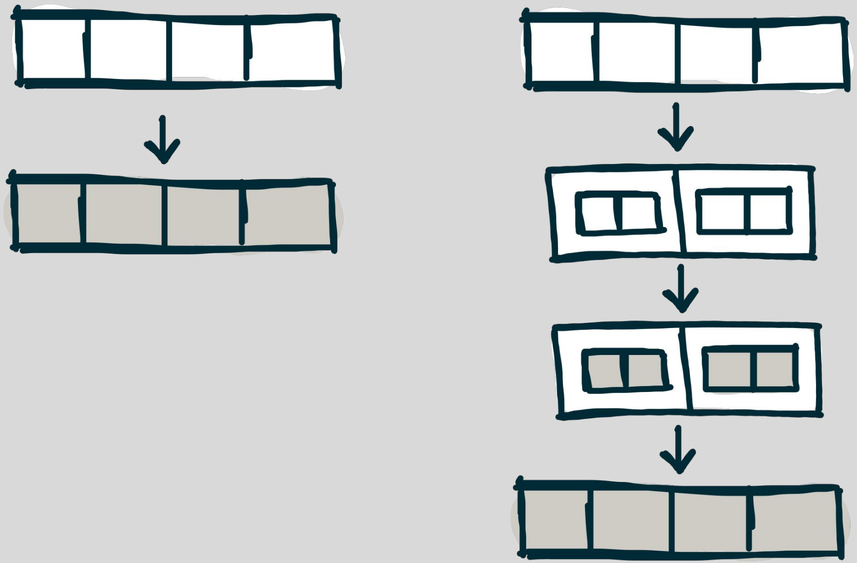
map`(f, A)`



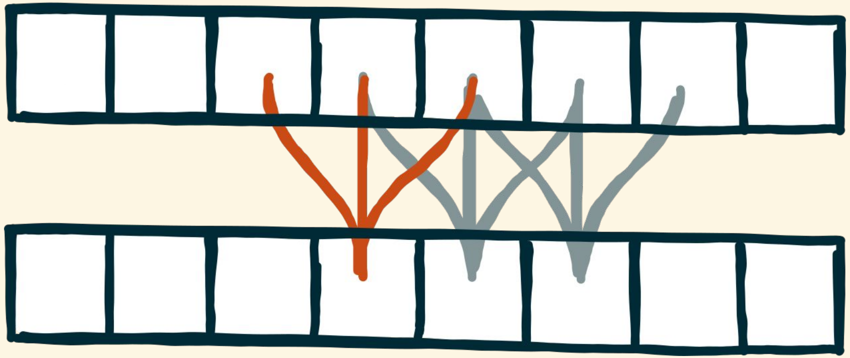
REUSING EXISTING REWRITE RULES

Divide & Conquer

```
map(f, A)  ↦  join(map(map(f),
                 split(n, A)))
```



OPTIMIZATION: OVERLAPPED TILING



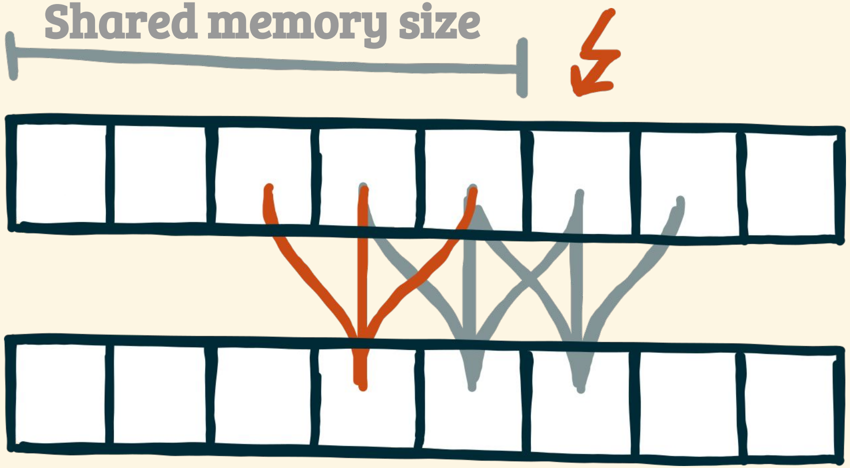
✓ **Exploit Locality**

Close neighborhoods share elements that can be grouped in tiles

✓ **Shared Memory**

Fast memory can be used to cache tiles

OPTIMIZATION: OVERLAPPED TILING



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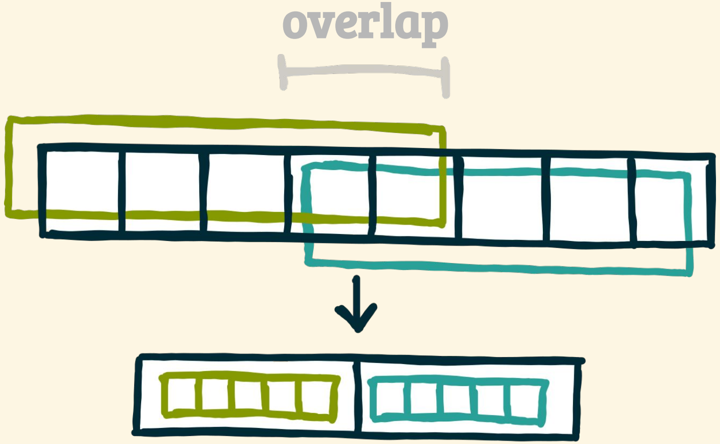
Optimization: Overlapped Tiling



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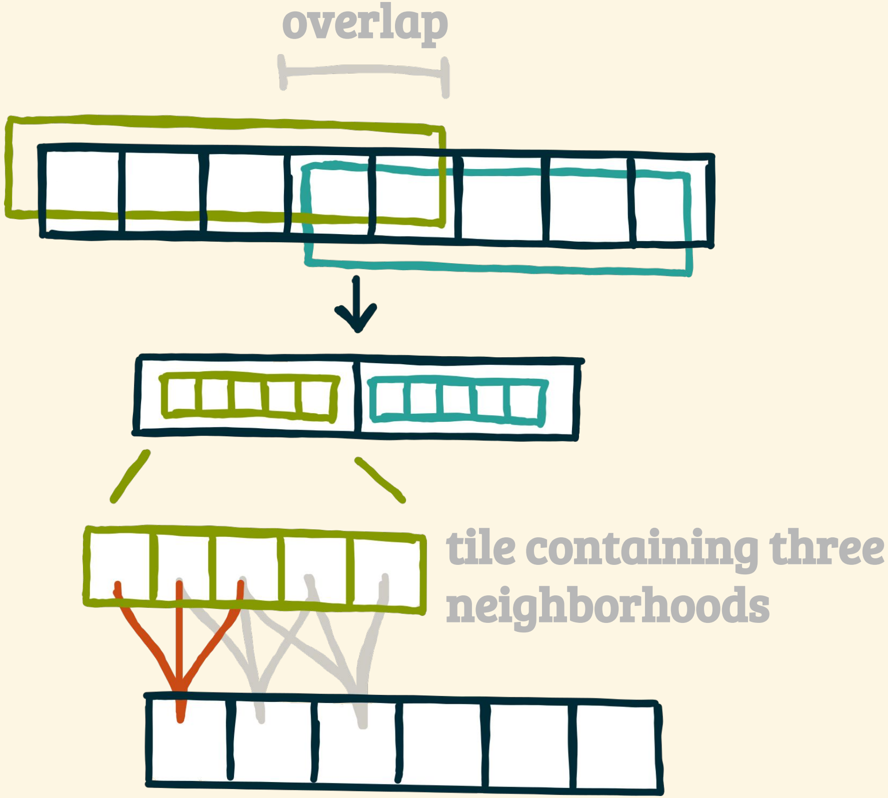
OPTIMIZATION: OVERLAPPED TILING



✓ **Exploit Locality**

Close neighborhoods share elements that can be grouped in tiles

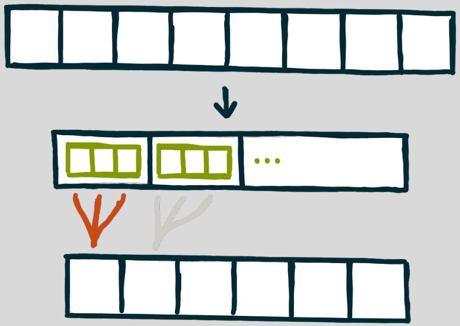
✓ **Shared Memory**

Fast memory can be used to cache tiles

Overlapped tiling as a rewrite rule

overlapped tiling rule

```
map(f, slide(3,1,input))
```

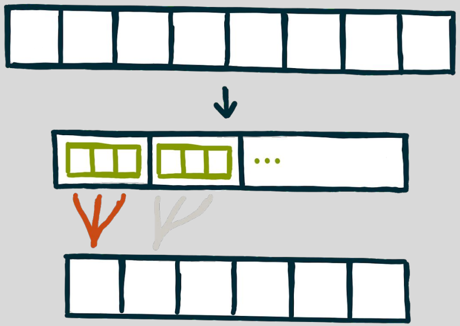


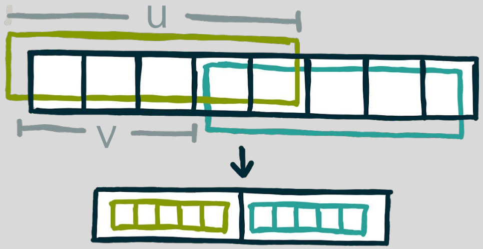
OVERLAPPED TILING AS A REWRITE RULE

overlapped tiling rule

map(f, ***slide***(3,1,input)) ↦

slide(u,v,input)

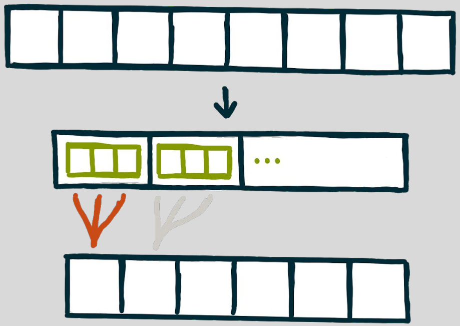


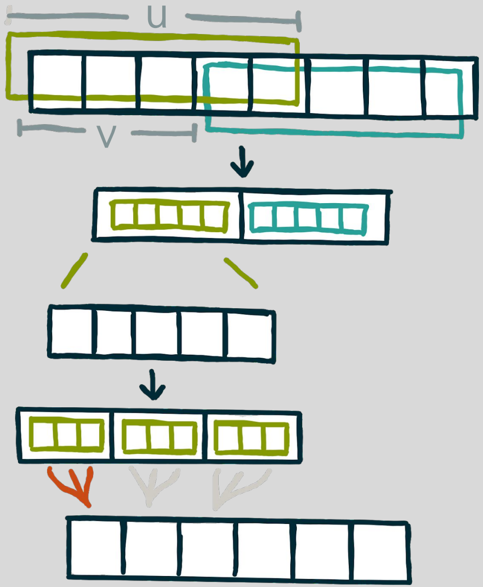


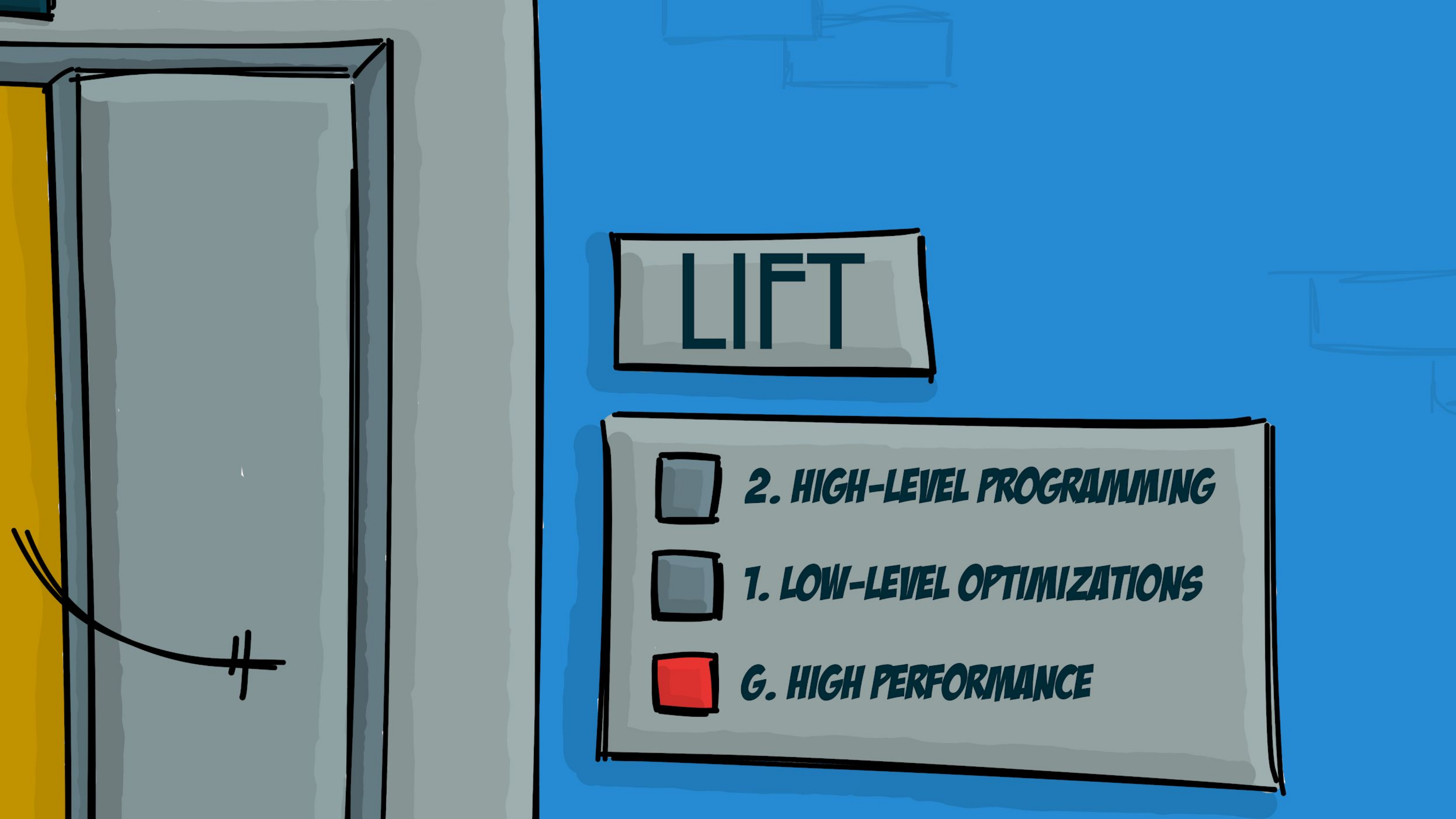
OVERLAPPED TILING AS A REWRITE RULE

overlapped tiling rule

map(f, *slide*(3,1,input)) ↦ *join*(*map*(tile ⇒
  map(f, *slide*(3,1,tile)),
  slide(u,v,input)))







LIFT

2. HIGH-LEVEL PROGRAMMING

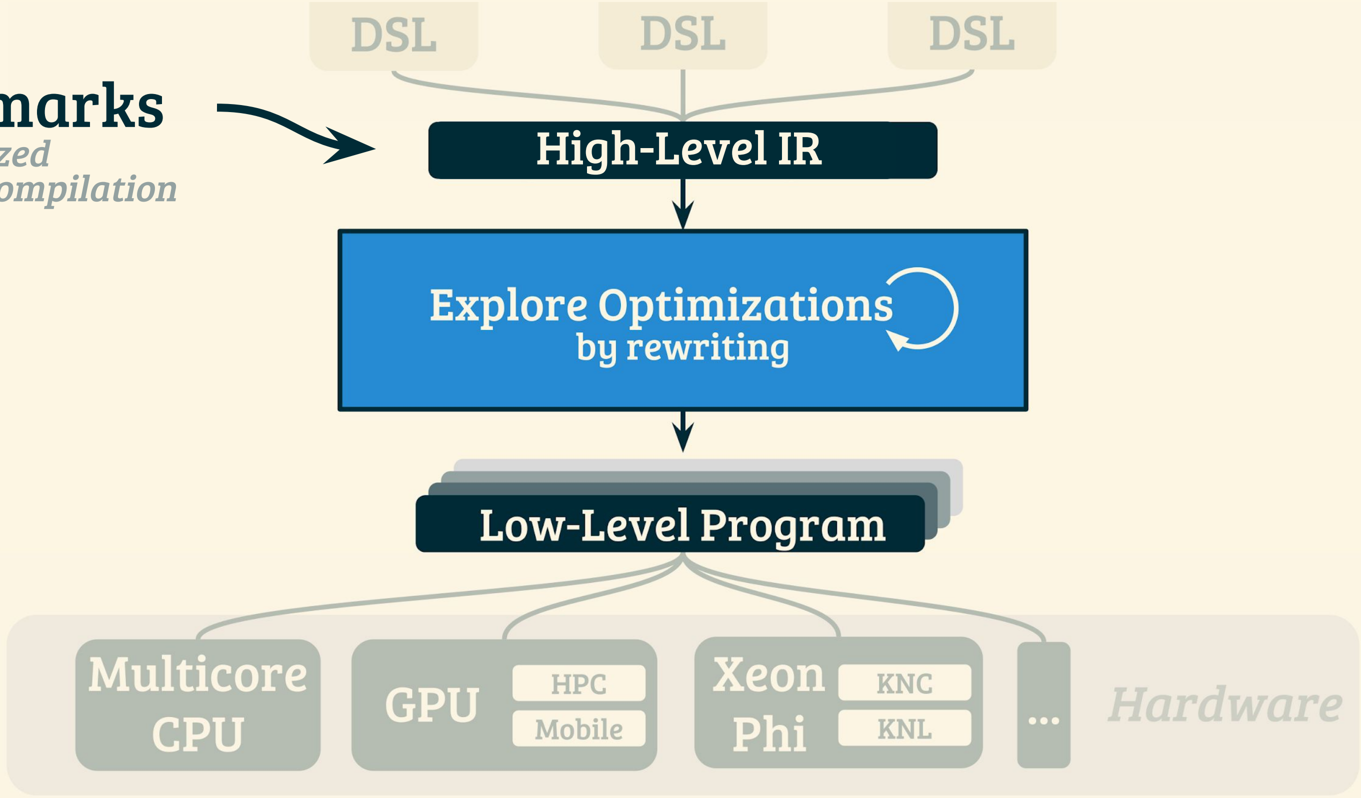
1. LOW-LEVEL OPTIMIZATIONS

G. HIGH PERFORMANCE

Experimental Evaluation

14 Benchmarks

6 hand-optimized
8 polyhedral compilation



Experimental Evaluation

14 Benchmarks

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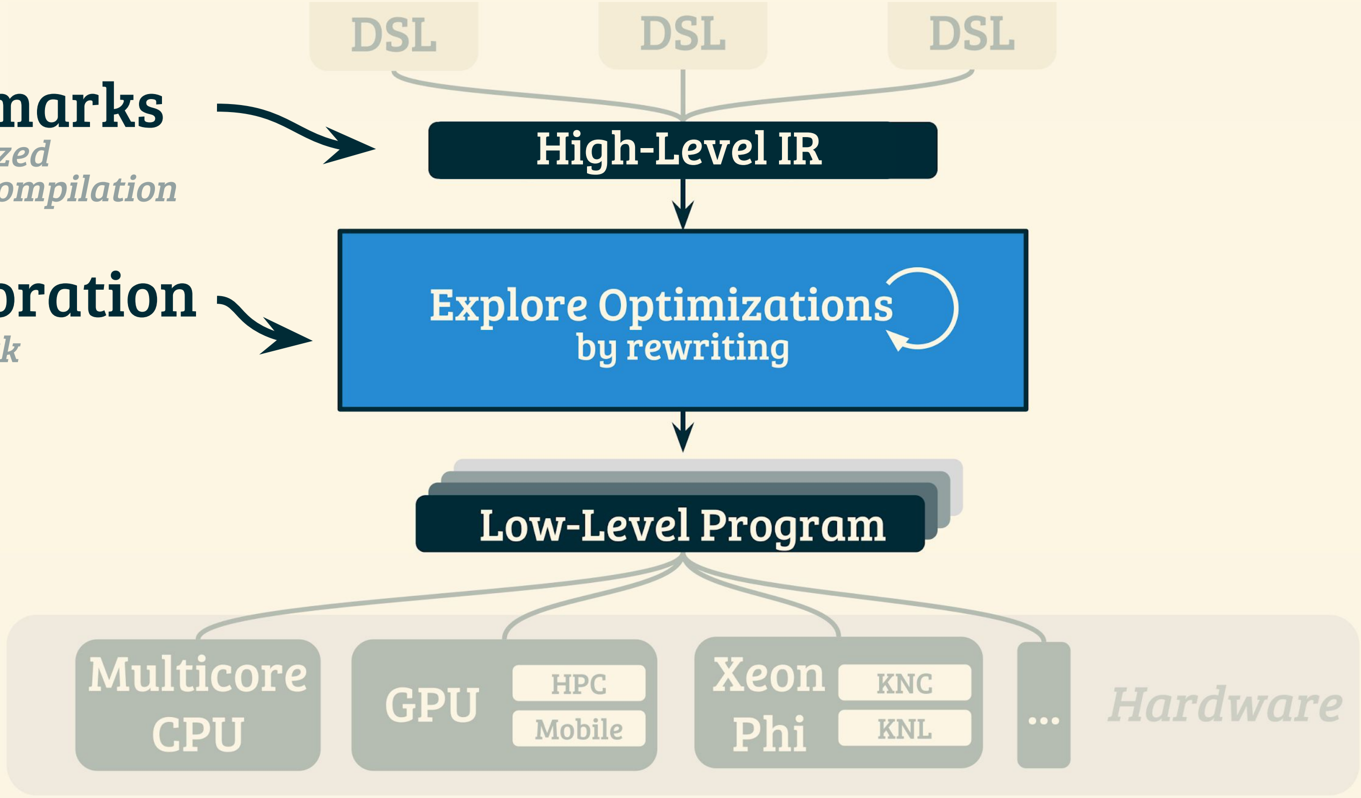
< 3h Exploration

per benchmark



Experimental Evaluation

14 Benchmarks

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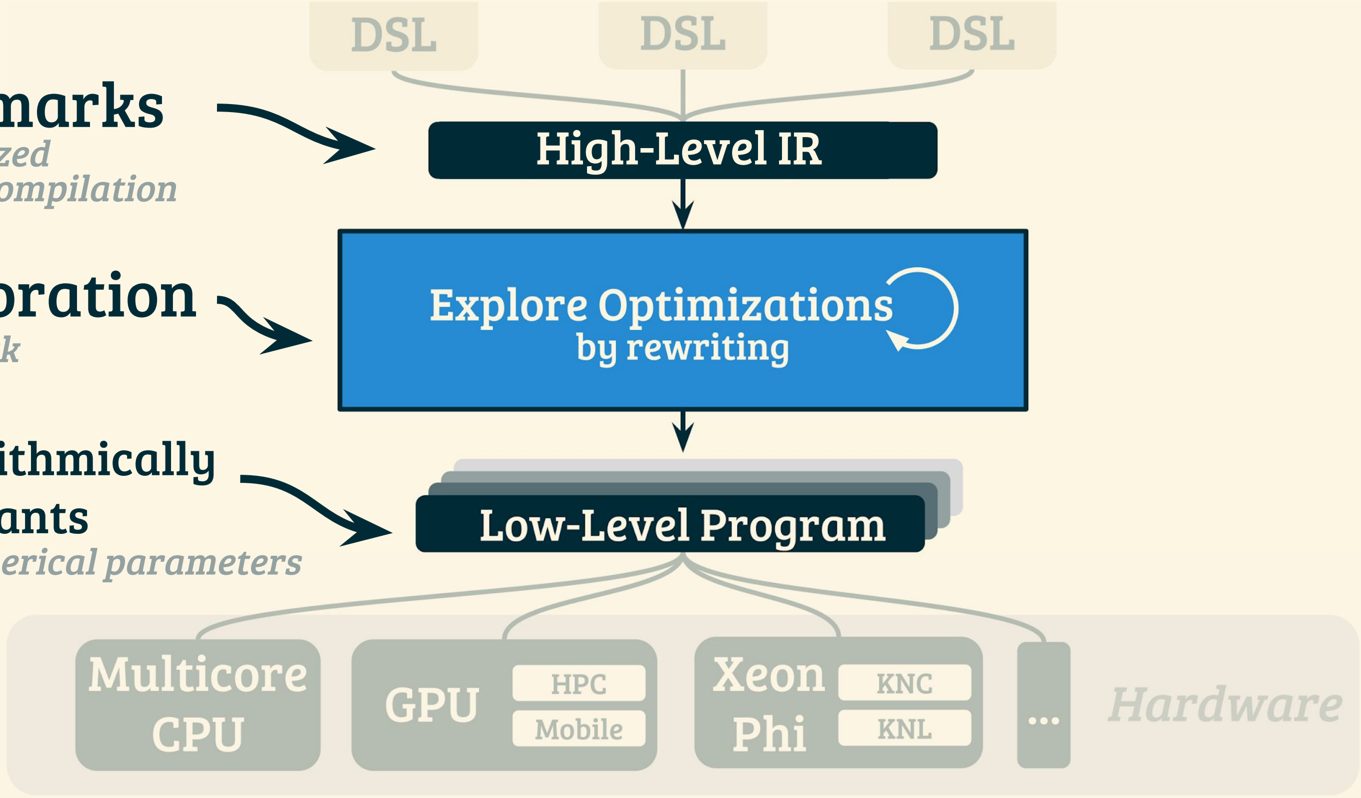
< 3h Exploration

per benchmark

up to 20 algorithmically different variants

+ auto-tuning of numerical parameters



DSL
DSL
DSL
High-Level IR
Explore Optimizations
by rewriting
Low-Level Program
Multicore CPU
GPU
HPC
Mobile
Xeon Phi
KNC
KNL
...
Hardware

Experimental Evaluation

14 Benchmarks

6 hand-optimized
8 polyhedral compilation

< 3h Exploration

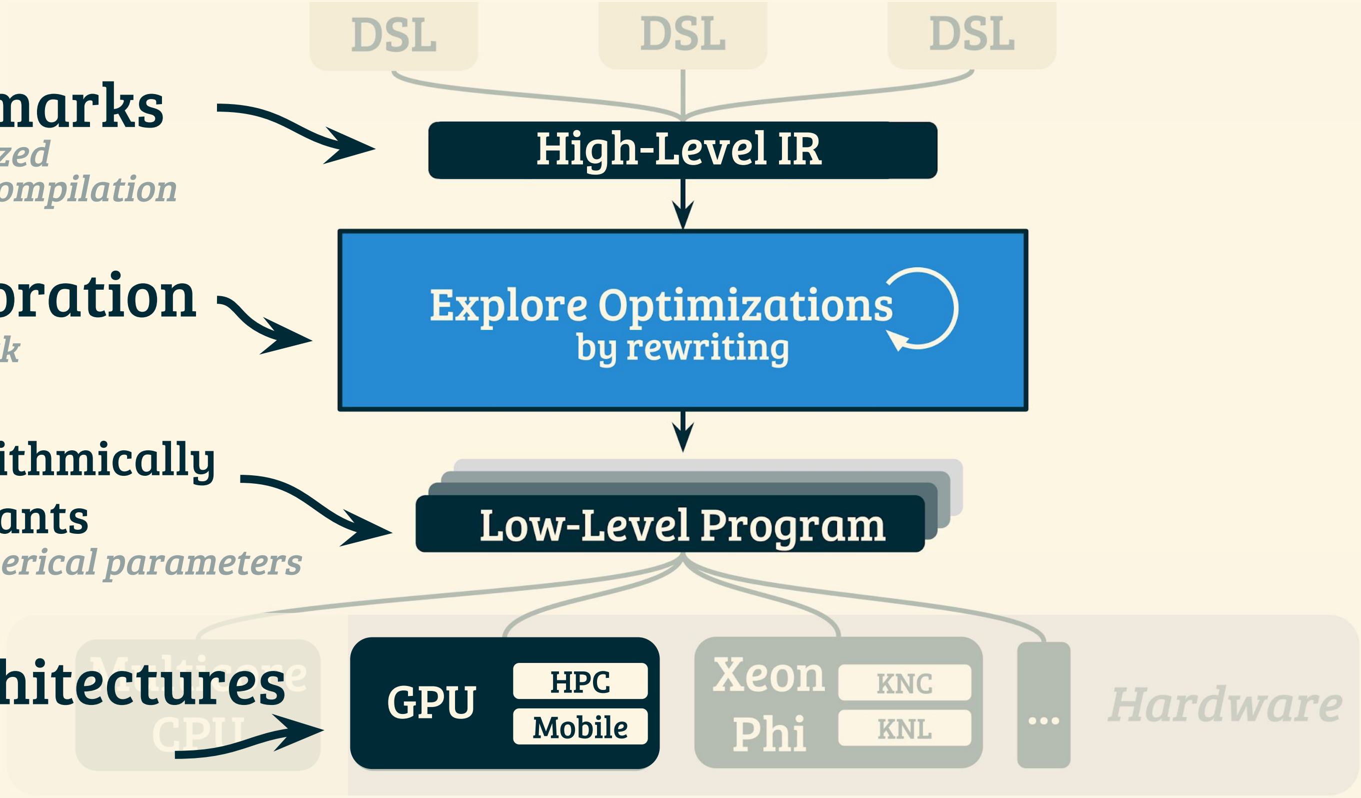
per benchmark

up to 20 algorithmically different variants

+ auto-tuning of numerical parameters

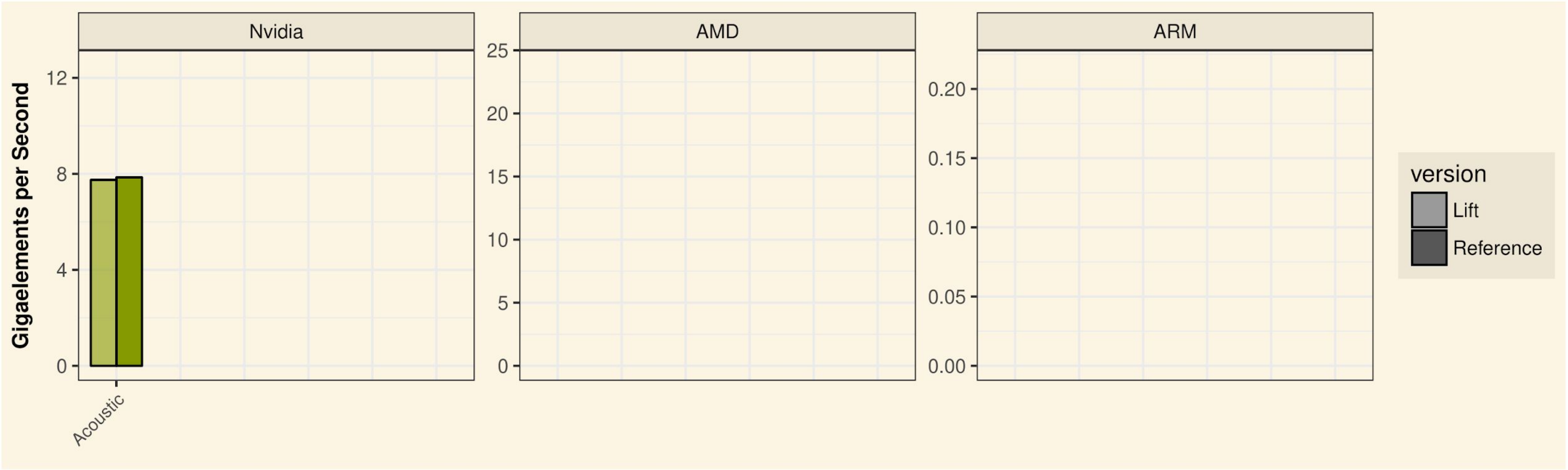
3 GPU Architectures

2 Desktop GPUs
1 Mobile GPU



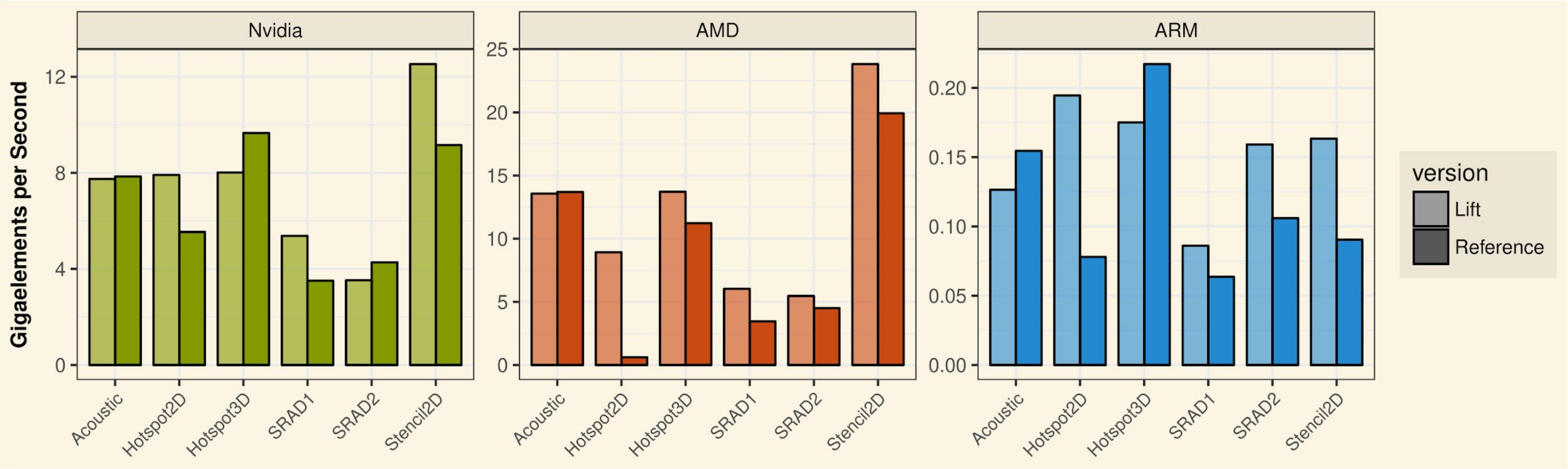
Comparison with hand-optimized codes

higher is better



COMPARISON WITH HAND-OPTIMIZED CODES

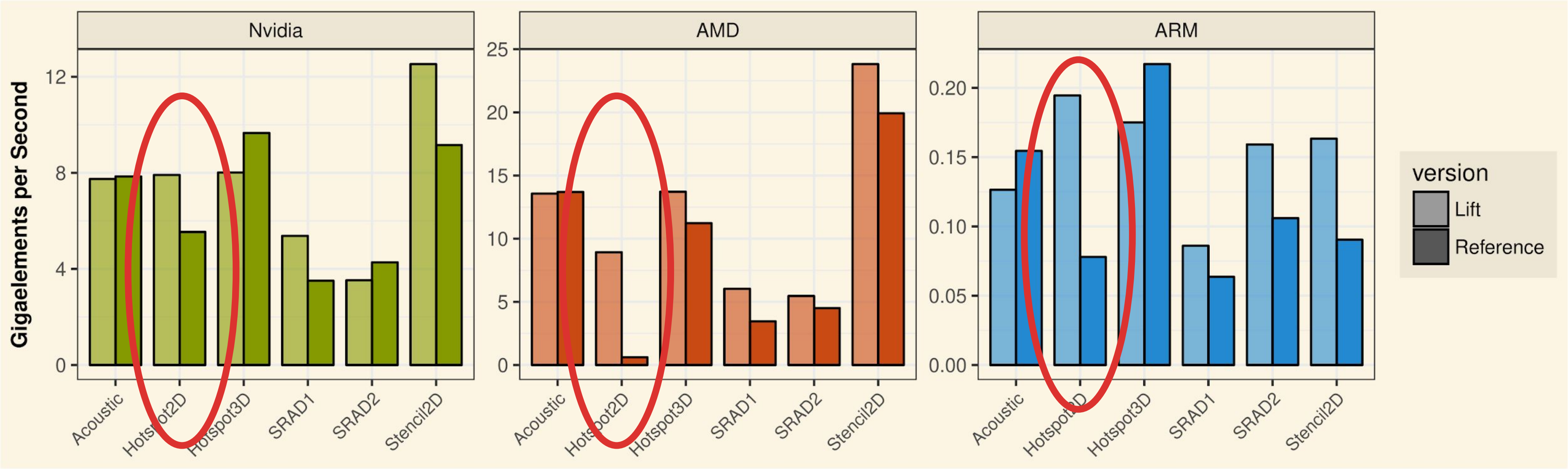
higher is better



Lift achieves the same performance
as hand optimized code

COMPARISON WITH HAND-OPTIMIZED CODES

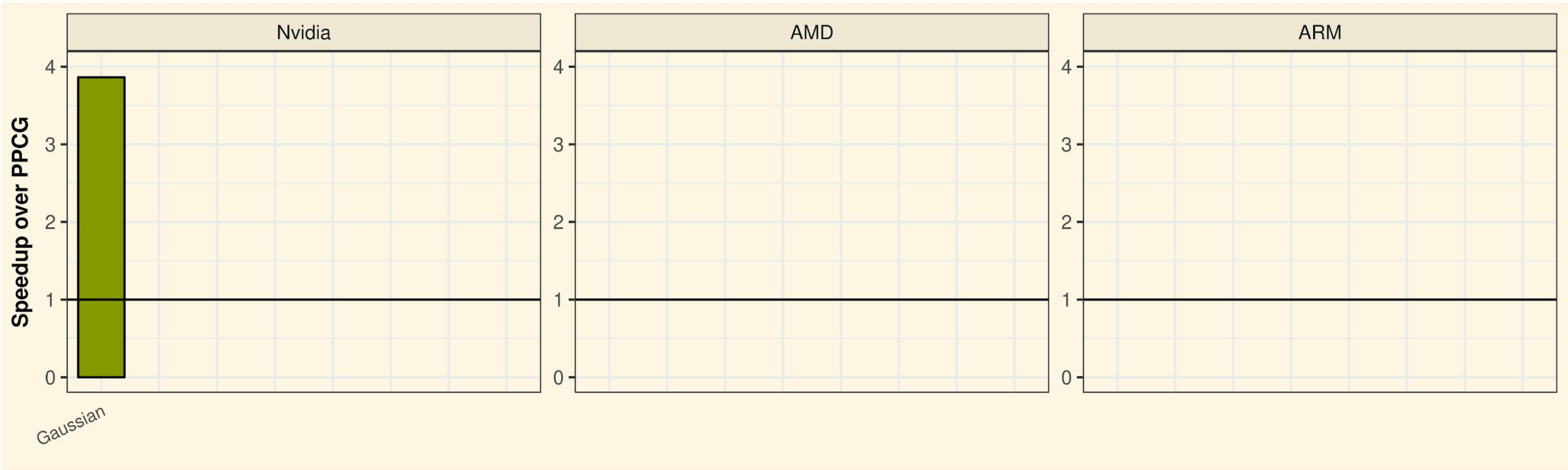
higher is better



Lift achieves the same performance as hand optimized code

Comparison with Polyhedral Compilation

higher is better



Comparison with polyhedral compilation

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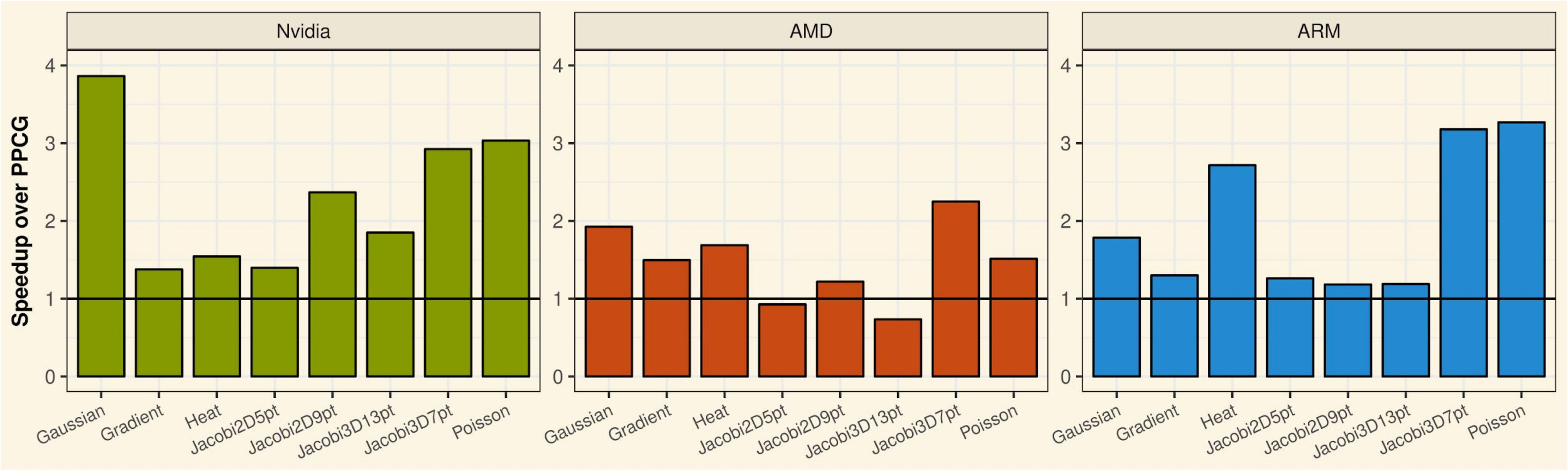


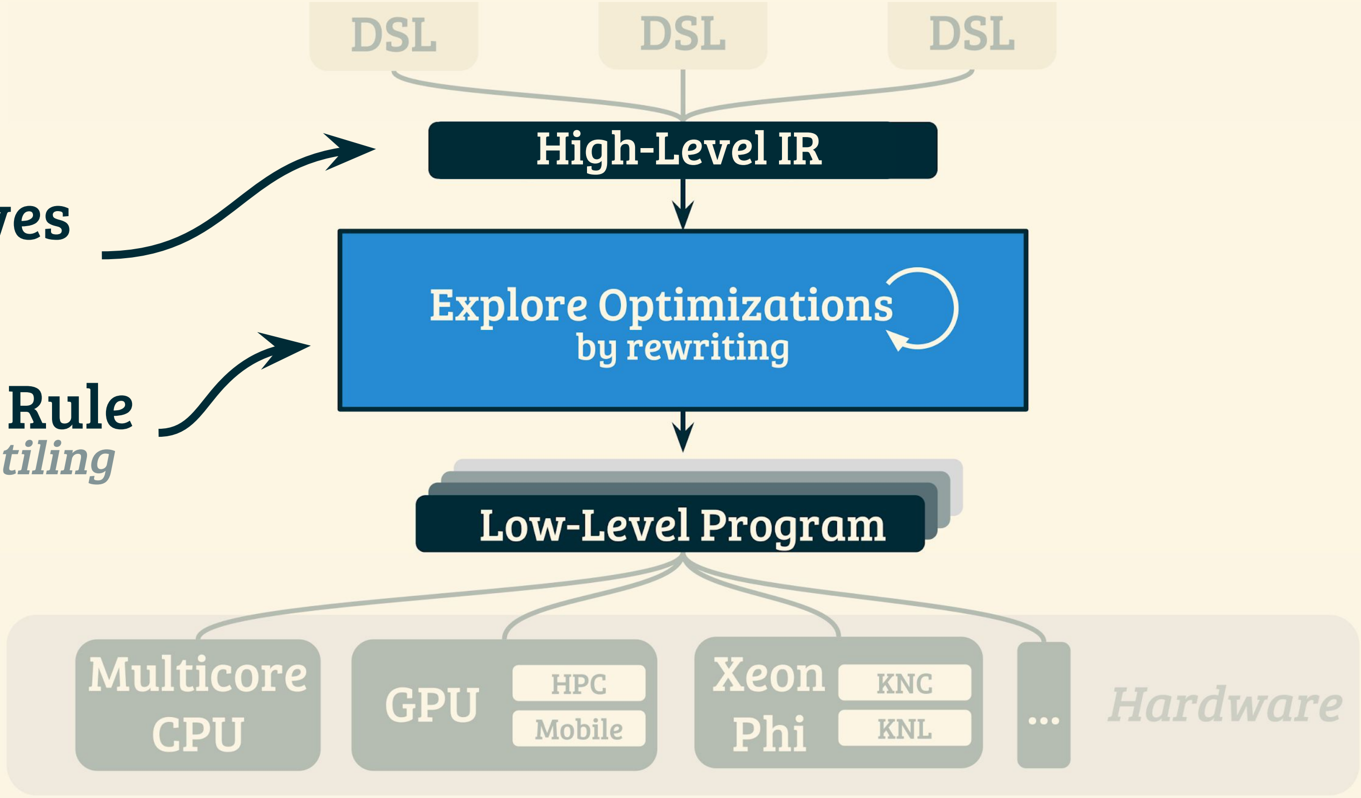
Lift outperforms state-of-the-art optimizing compilers

STENCIL COMPUTATIONS IN LIFT

We added:

2 Primitives
pad, *slide*

1 Rewrite Rule
overlapped tiling



DSL

DSL

DSL

High-Level IR

Explore Optimizations
by rewriting

Low-Level Program

Multicore
CPU

GPU

HPC

Mobile

Xeon
Phi

KNC

KNL

...

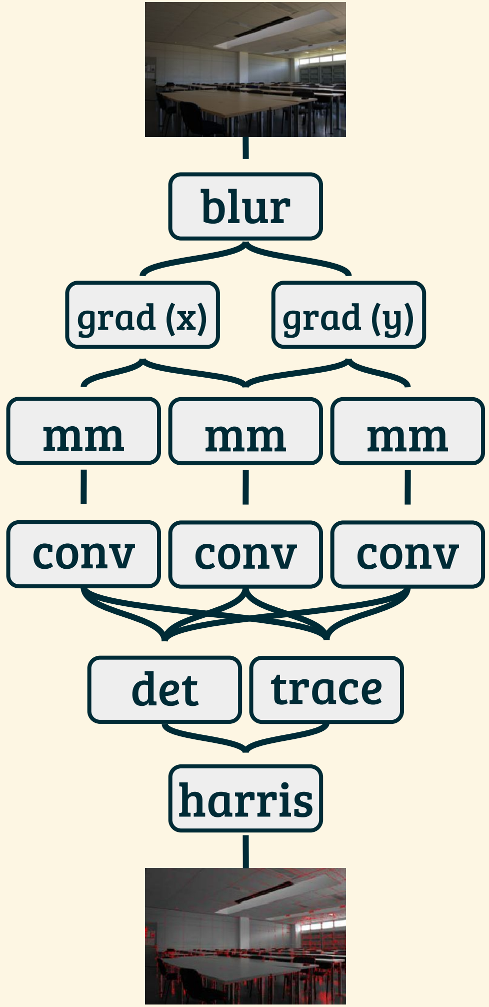
Hardware

A STEP FURTHER

towards multi-kernel stencil computations

conv

```
def conv =
 fun(A =>
  map2D(multWeights,
   slide2D(3,1,
    pad2D(1,1,clamp,A))))
```



A STEP FURTHER

towards multi-kernel stencil computations

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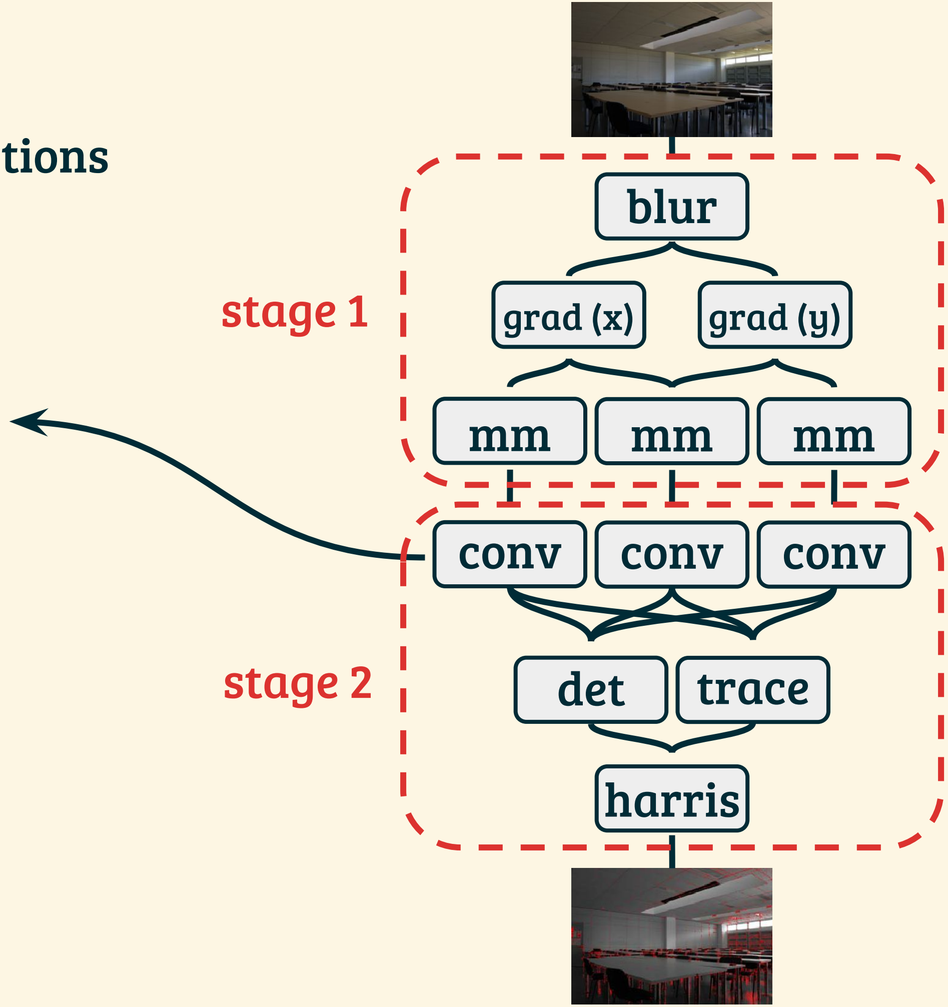

A STEP FURTHER

towards multi-kernel stencil computations

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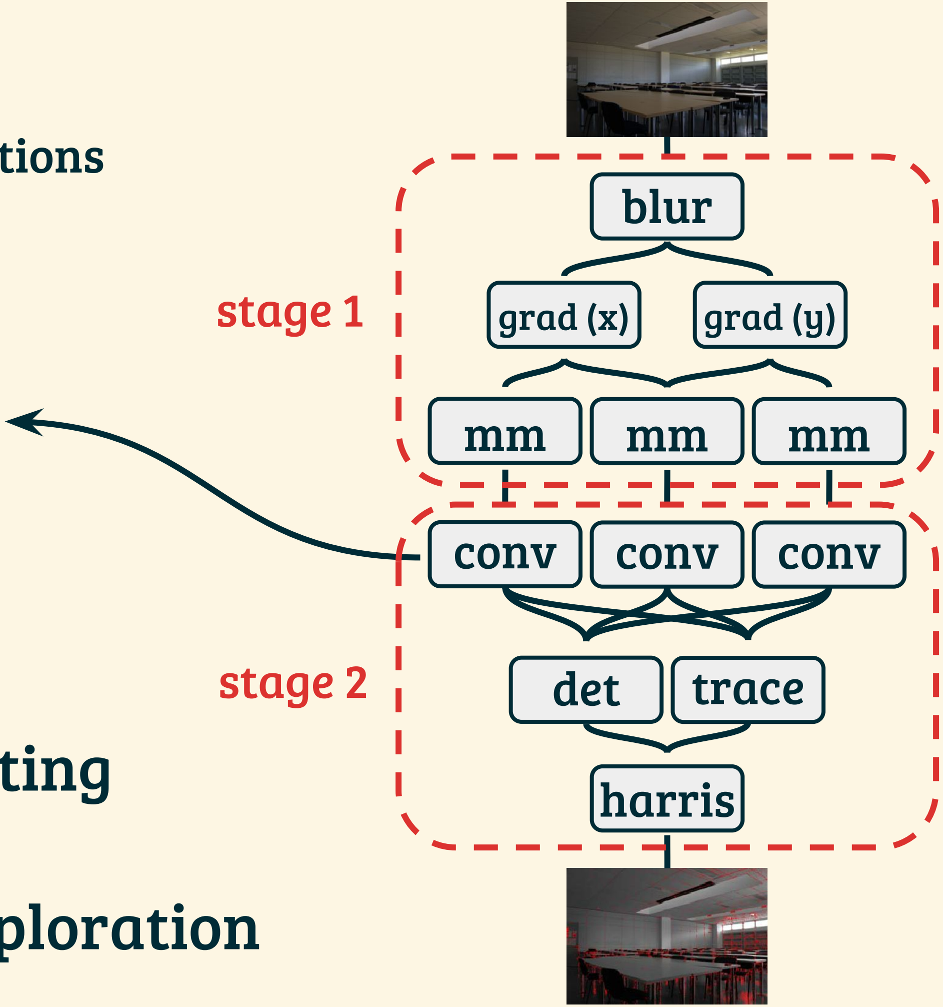
```



Kernel Fusion via Rewriting

Guided Search Space Exploration

LIFT IS OPEN SOURCE!

Artifacts Available acm

Artifacts Evaluated Reusable acm

Results Replicated acm

more info at:

lift-project.org

Paper

Artifacts Available acm CGO Artifact

Source Code

Best Paper Award (CGO'18)

TO BE CONTINUED...

Bastian Hagedorn: b.hagedorn@wwu.de