SkePU

ida.liu.se/labs/pelab/skepu/

Introduction & Tutorial

August Ernstsson Christoph Kessler
{firstname.lastname}@liu.se
Linköping University, Sweden

LINKÖPING UNIVERSITY

exa2pro
Enhancing Programmability and boosting Performance Portability For Exascale Computing Systems

Overview

- Introduction and history
- SkePU interface
- Installation
- Skeletons in depth
  - Map
  - Reduce
  - MapReduce
  - Scan
  - MapOverlap
- Preview: Future SkePU
- Demonstration, Outlook, Discussion…

Skeleton Programming

Skeleton Programming :: Motivation

Programming parallel systems is hard!

- Resource utilization
- Synchronization, Communication
- Memory consistency
- Different hardware architectures, heterogeneity

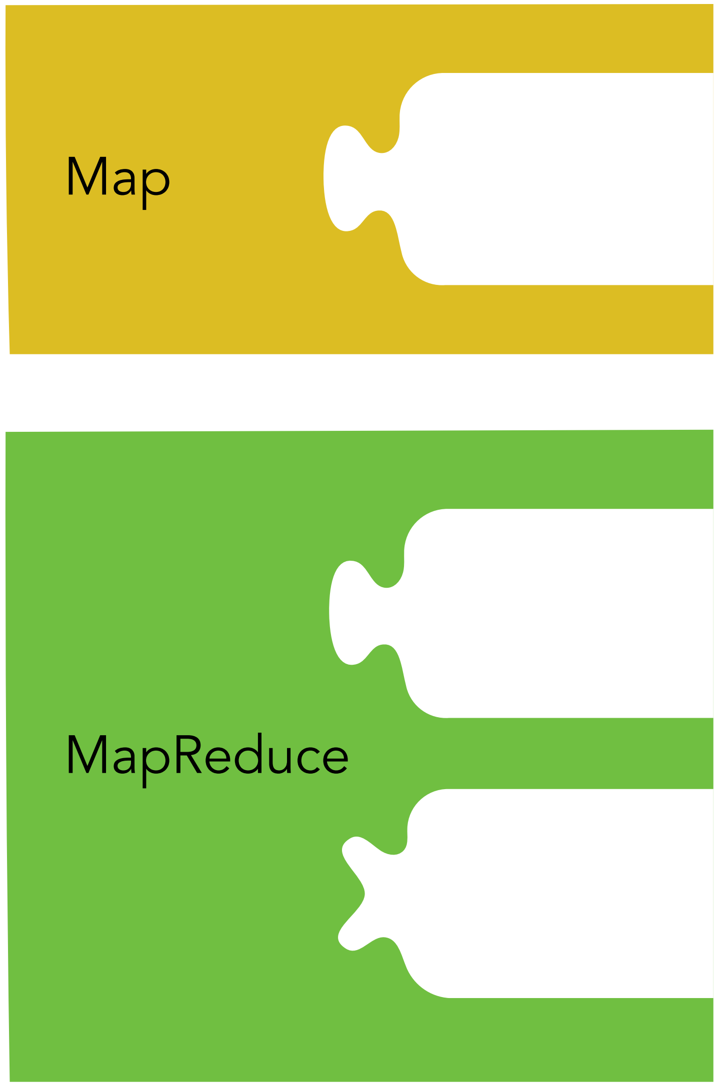
Skeleton programming (algorithmic skeletons)

- A high-level parallel programming concept
- Inspired by functional programming
- Generic computational patterns
- Abstracts architecture-specific issues

Skeletons

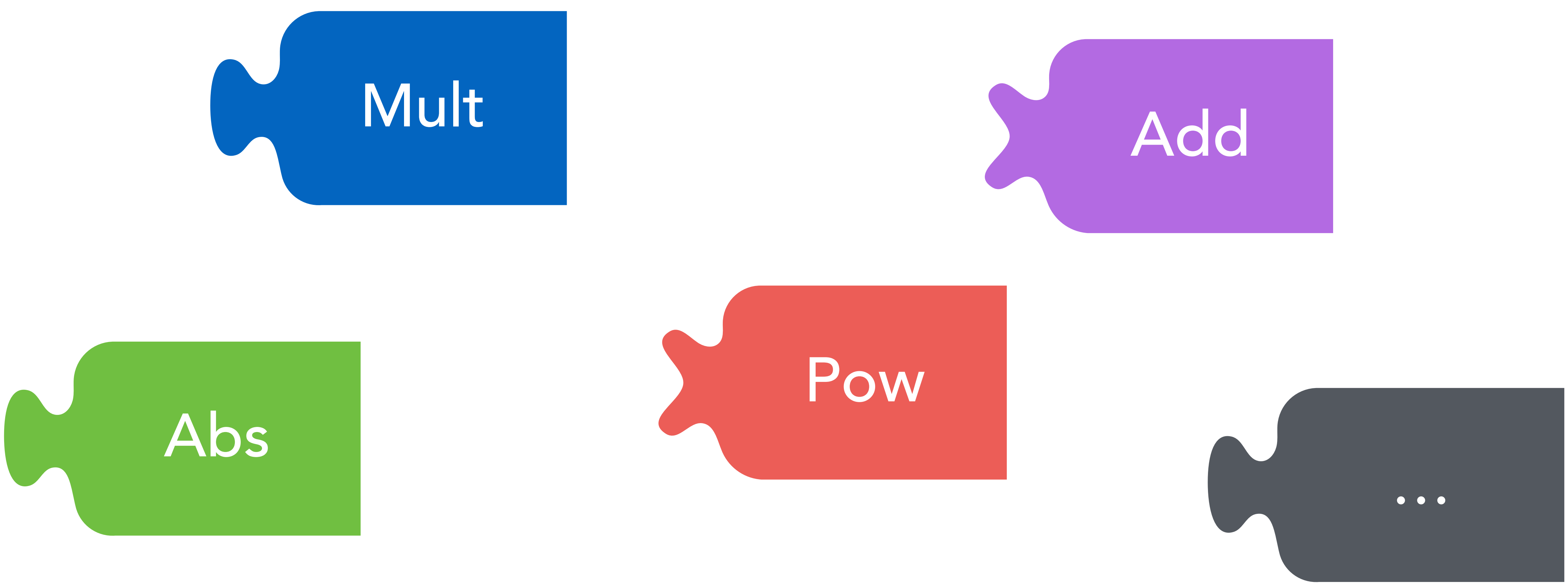
Parametrizable higher-order constructs

- Map
- Reduce
- MapReduce
- Scan
- and others



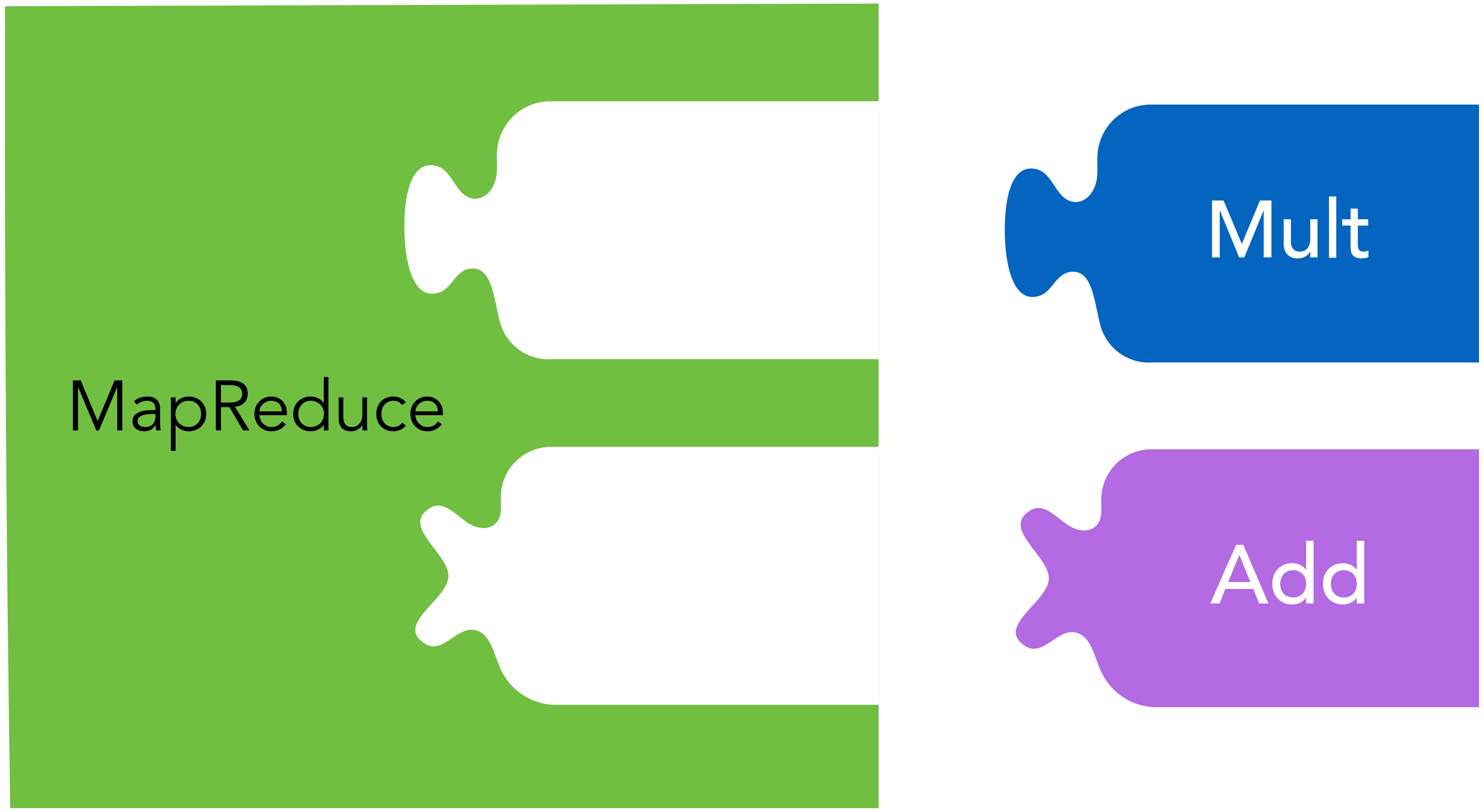
User functions

User-defined operators



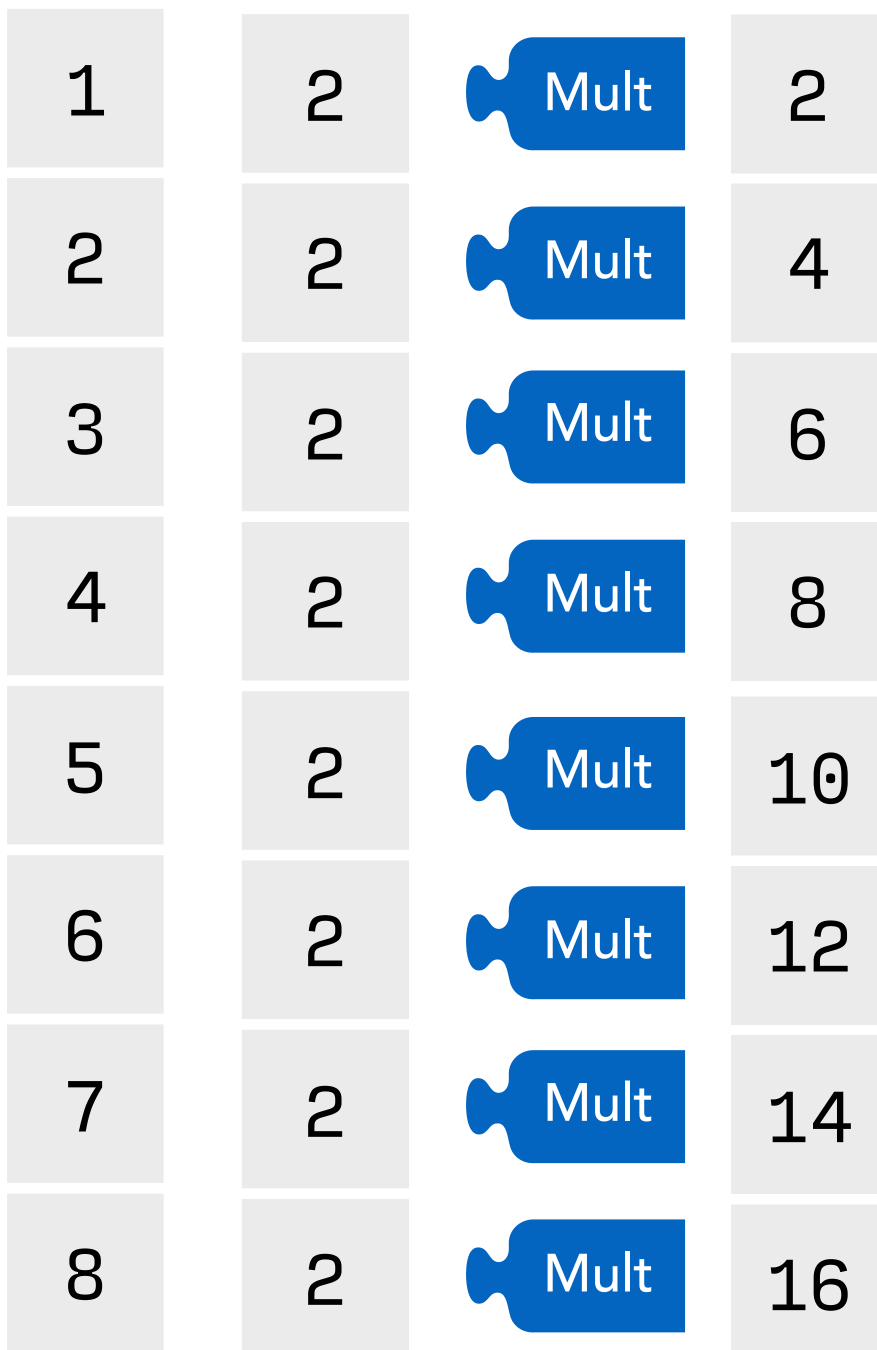
Skeleton parametrization example

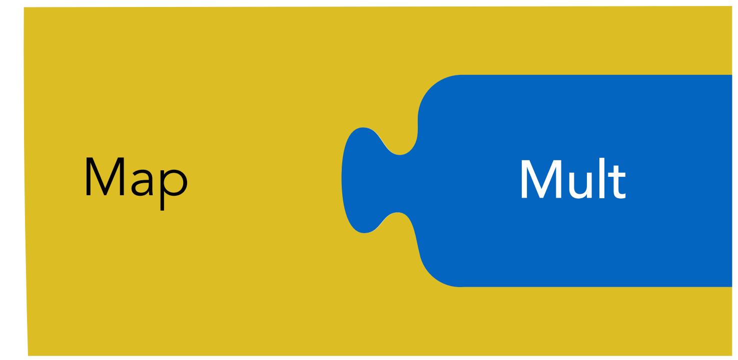
Dot product operation



Skeleton Programming :: Map

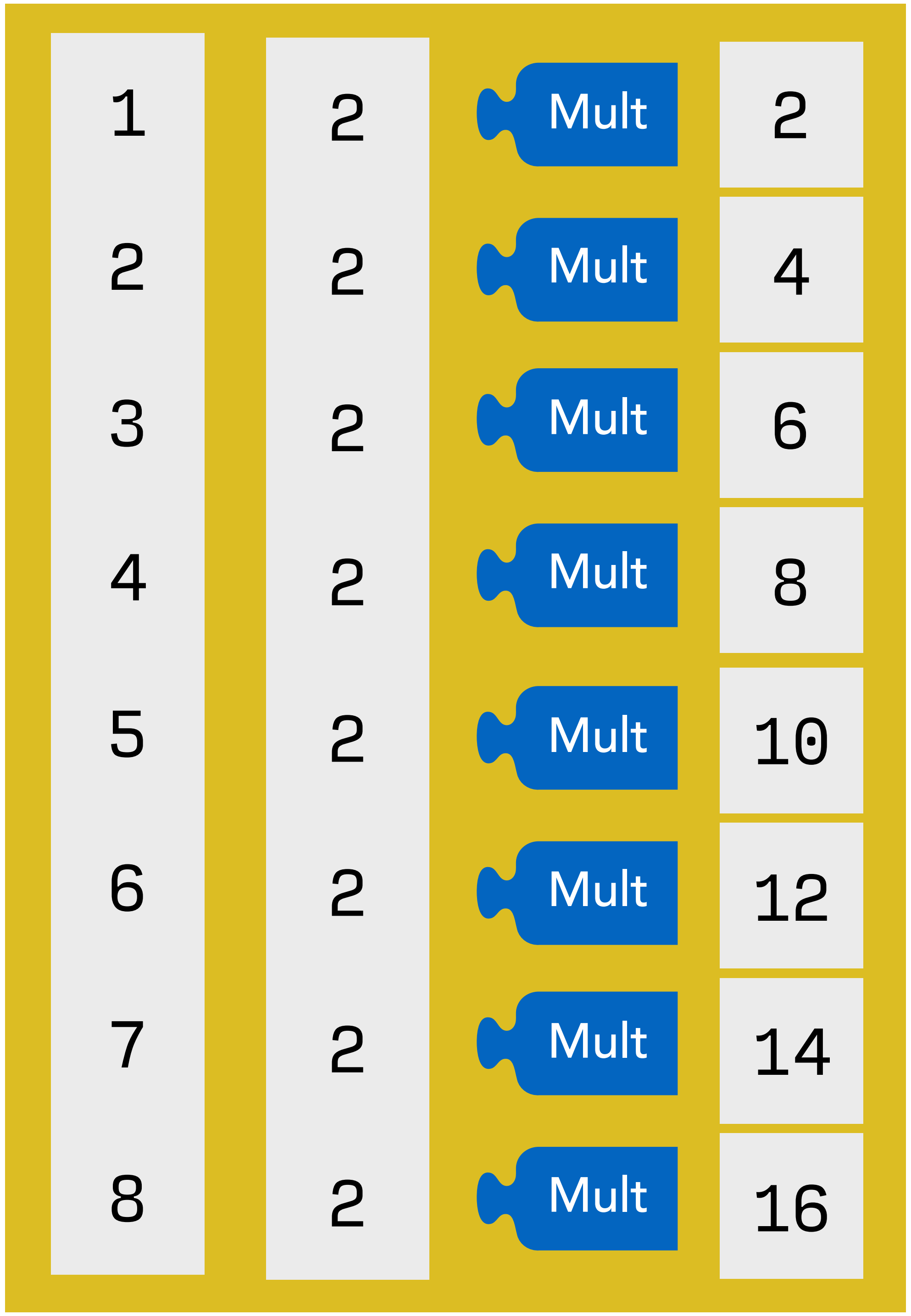
Sequential algorithm

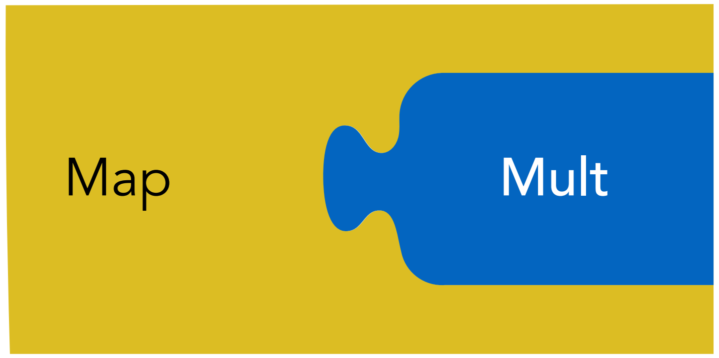




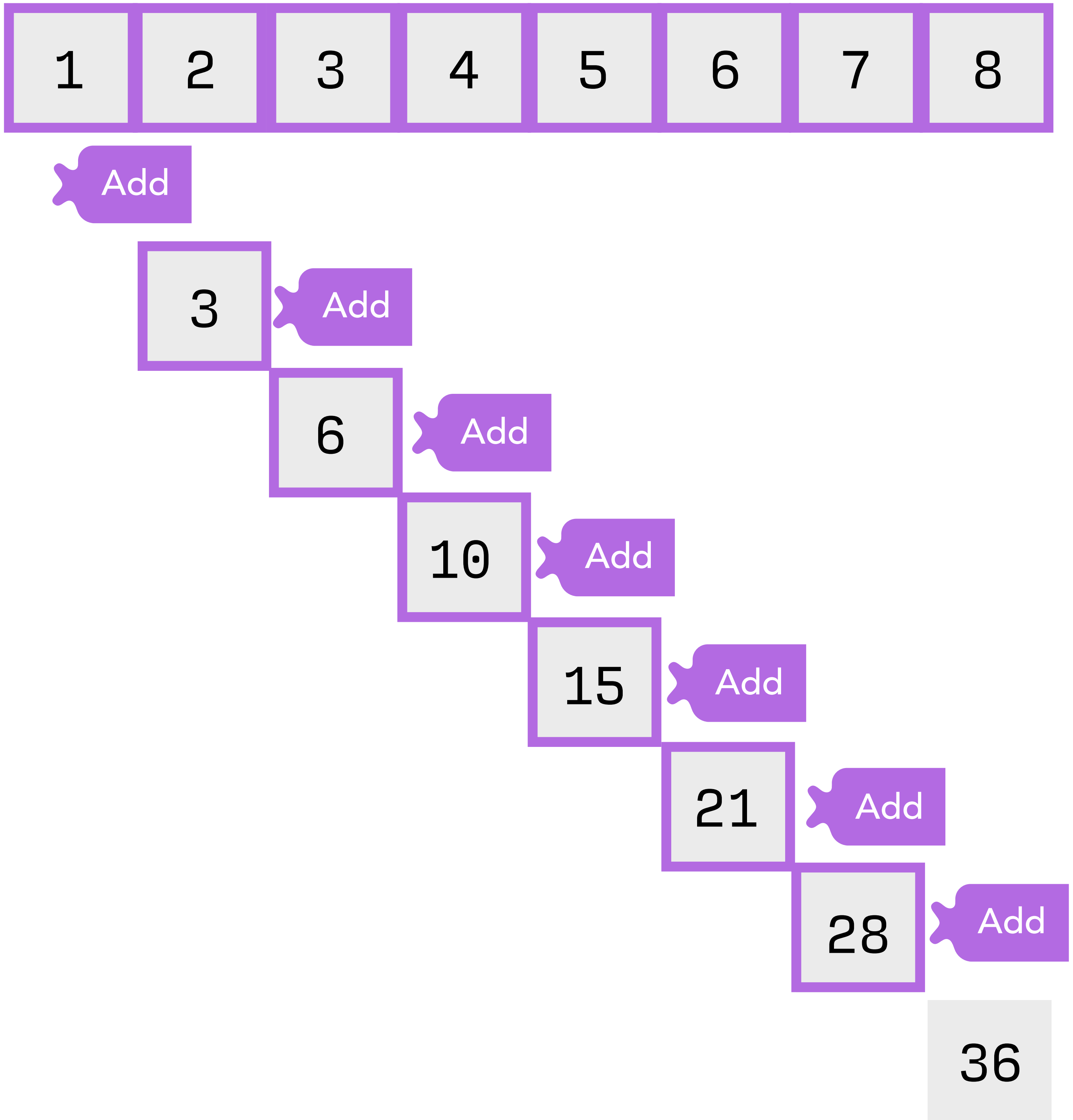
Skeleton Programming :: Map

Parallel algorithm



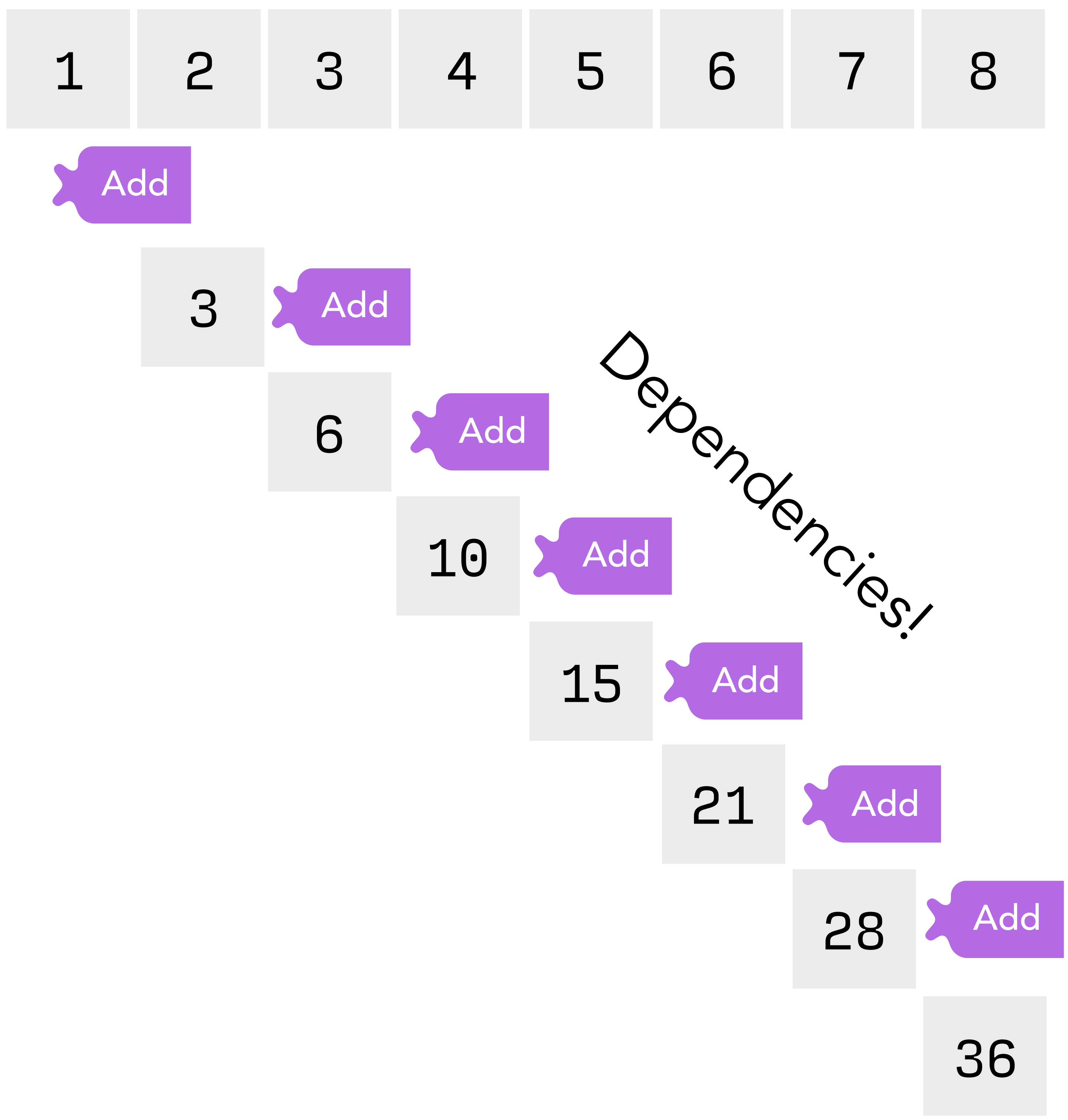


Sequential algorithm

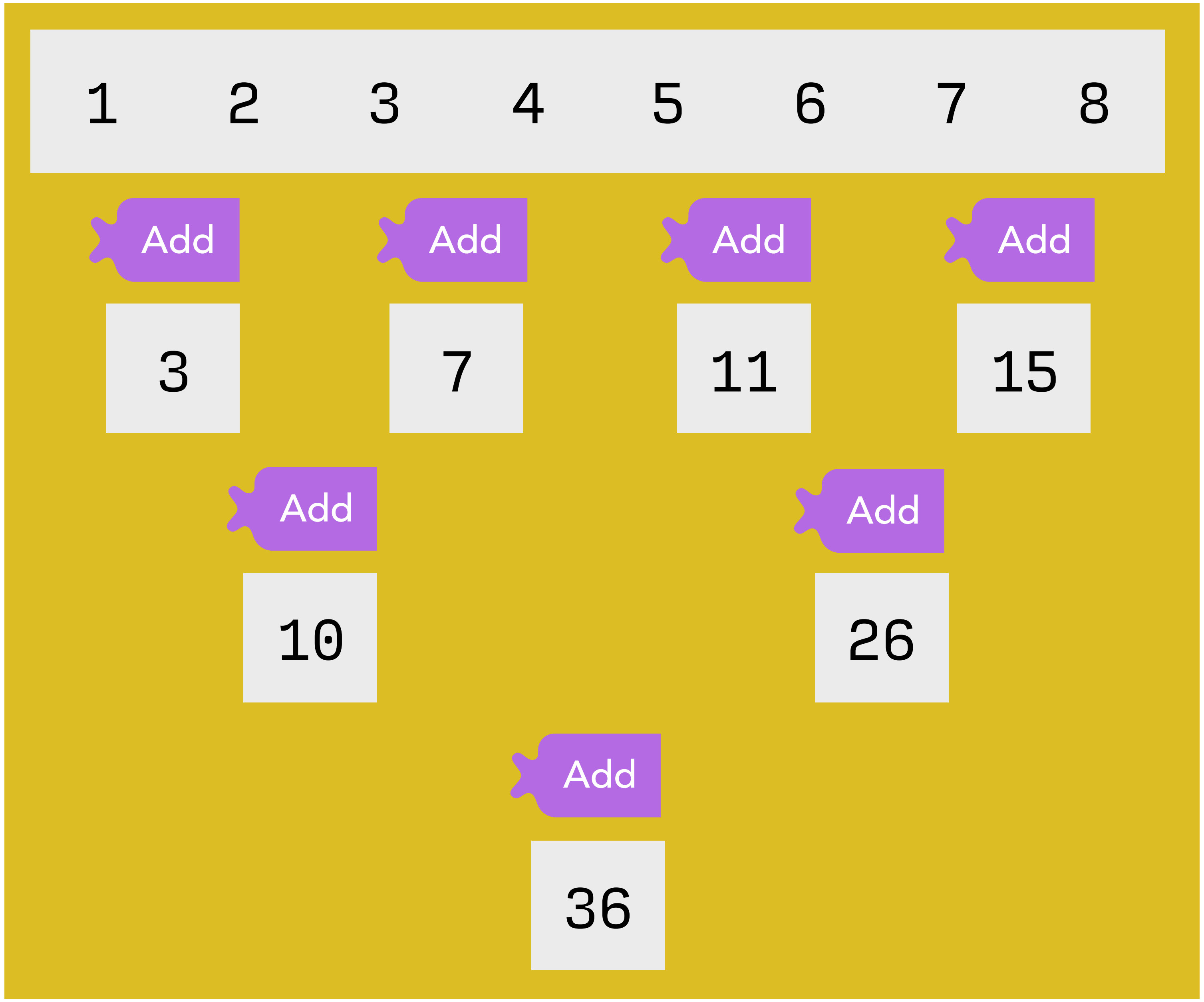


Skeleton Programming :: Reduce

Parallel algorithm?



Parallel algorithm
(assuming associativity)



SkePU

But First: Modern C++

- SkePU uses ”modern” C++

```
// ”auto” type specifier
auto addOneMap = skepu2::Map<1>(addOneFunc);

skepu2::Vector<float> input(size), res(size);
input.randomize(0, 9);

// Lambda expression
auto dur = skepu2::benchmark::measureExecTime([&]
{
    addOneMap(res, input);
});
```

capture by reference

- Implementation reliant on variadic templates, template metaprogramming, and other C++11 features

Features

- ✓ Efficient parallel algorithms
- ✓ Memory management and data movement
- ✓ Automatic backend selection and tuning

History

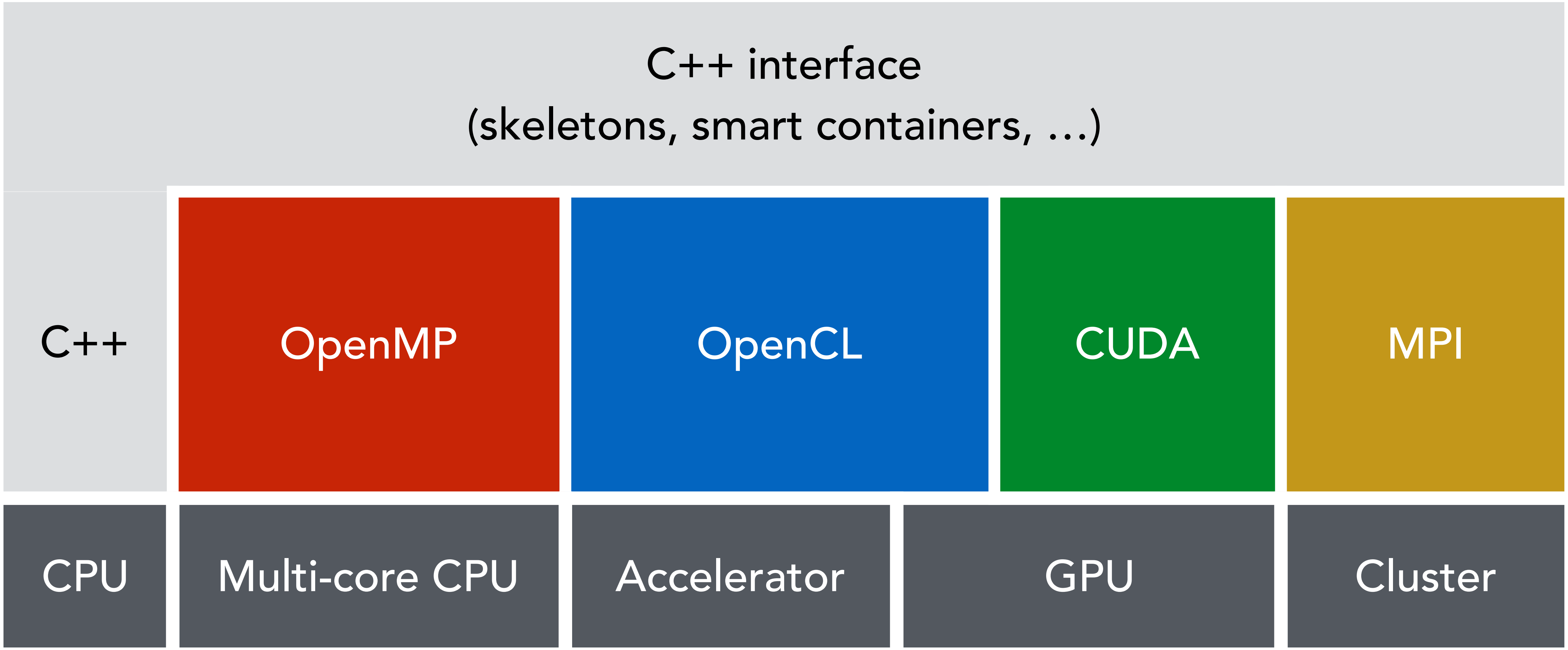
- **SkePU 1**, released **2010**
  - C++ template-based interface (limited arity)
  - Multi-backend using macro-based code generation
- **SkePU 2**, released **2016**
  - C++11 *variadic* template interface (flexible arity)
  - Multi-backend using source-to-source precompiler
- **SkePU 3**, in development for **2020**
  - Expanding skeleton set, container set, and expressivity

Features

- Skeleton programming framework
  - C++11 **library** with skeleton and data container classes
  - A **Clang**-based source-to-source **pre-compiler**
- Smart containers: `Vector<T>, Matrix<T>`
  - In development: `SparseMatrix<T>`
- For **heterogeneous multicore** systems
  - Multiple backends
- Active research tool with a number of publications 2010-2019 (see website)

- **Skeletons provided by SkePU**
  - Map
  - Reduce
  - MapReduce
  - Scan
  - MapOverlap
  - (In development) MapPairs

Backend Architecture



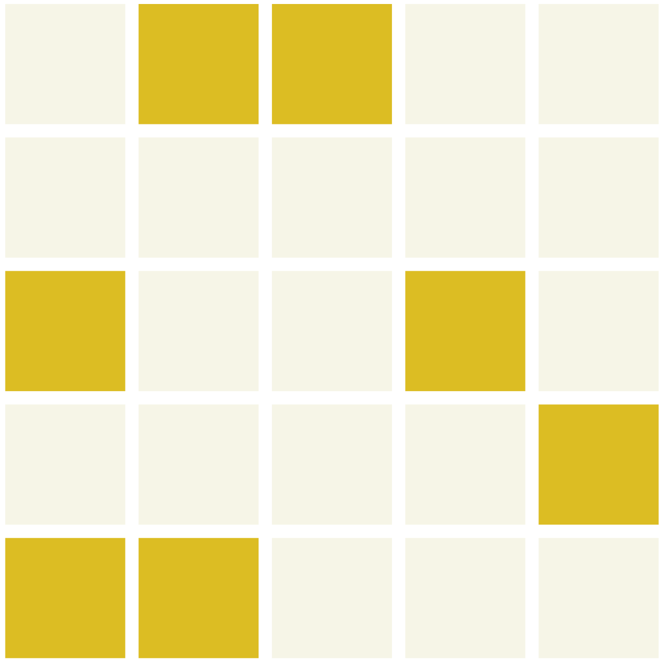
Internal prototype

Smart Containers

Vector

Matrix

Sparse matrix

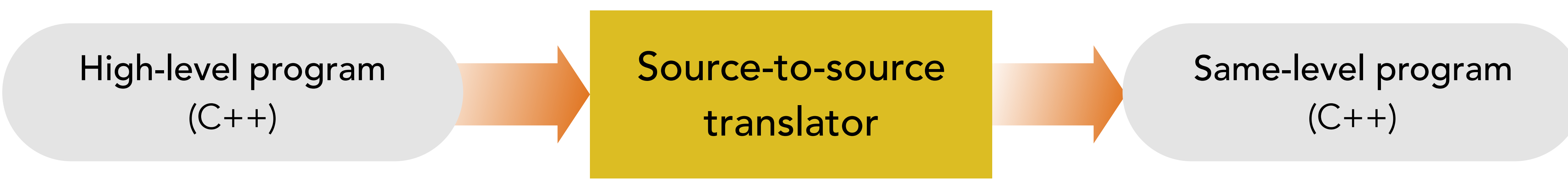


Smart Containers

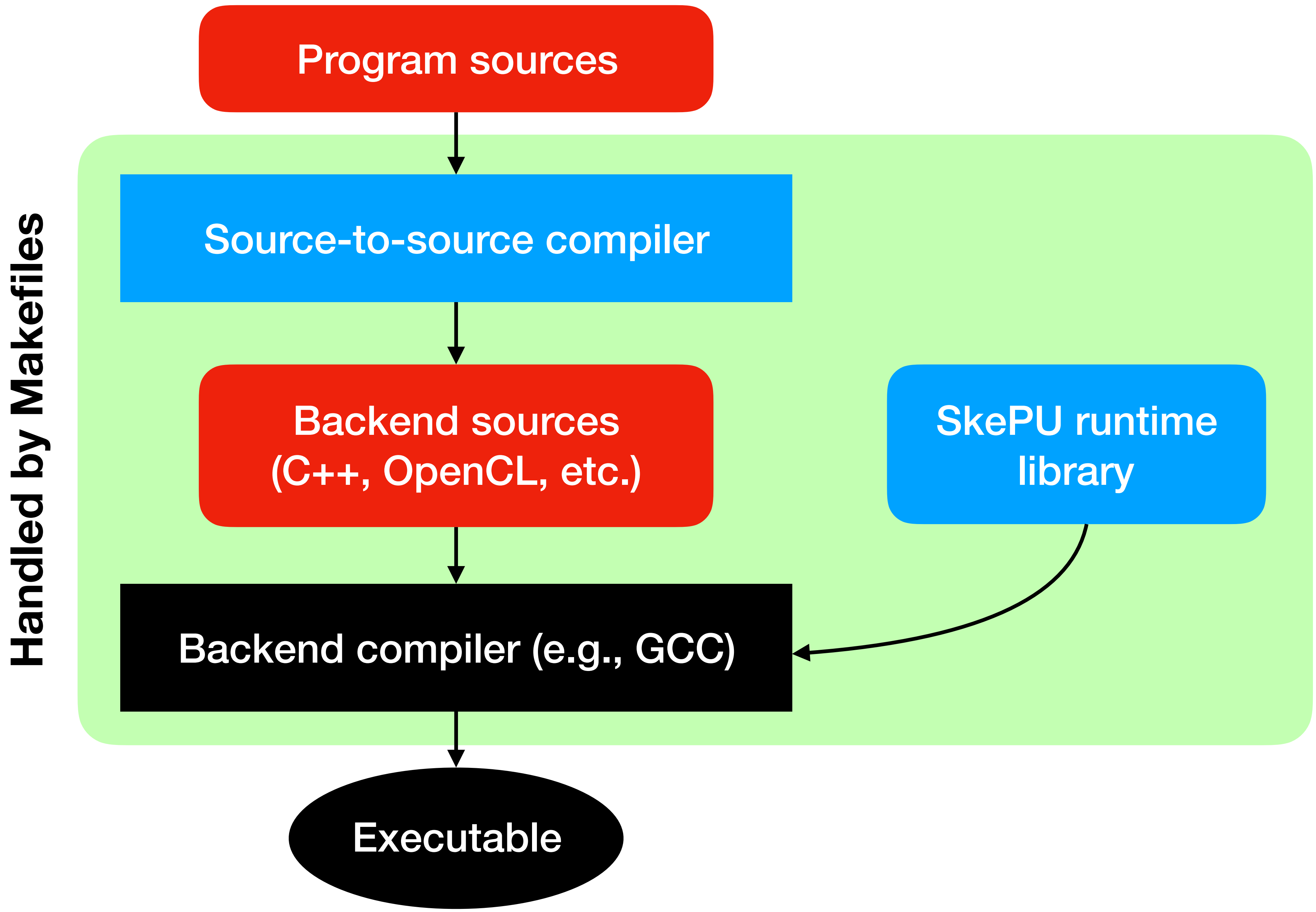
- C++ template class instance
- Contains:
  - CPU memory buffer **pointer** (alt. StarPU handles)
  - Size information (size, width/height)
  - OpenCL/CUDA/MPI **handles**
  - Consistency states
- Template type can be **custom struct**, but be careful!
  - Data layout not verified across backends/languages

Using SkePU

Source-to-Source Translation



Compilation Architecture



Installation

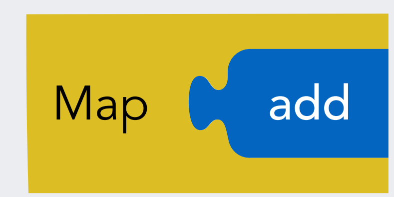
- Two main installation options:
  - Use provided **pre-built** pre-compiler tool and library (For 64-bit Linux systems)
  - Use installation script to **download and build** pre-compiler (Requires time and disk space for LLVM/Clang source trees)

See website: https://www.ida.liu.se/labs/pelab/skepu/

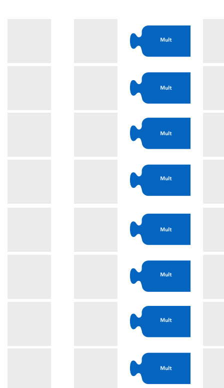
Syntax

```
int add(int a, int b, int m)
{
    return (a + b) % m;
}
```


```
auto vec_sum = Map<2>(add);
```




```
vec_sum(result, v1, v2, 5);
```



User Functions


```
int add(int a, int b, int m)
{
    return (a + b) % m;
}
```

- User functions are C++ (rather, C) functions
- The signature is analyzed by the pre-compiler to extract the skeleton signature
- Each skeleton has their own expected patterns for UF parameters (but the general structure is shared)
- The UF body is **side-effect free** C (compatible with CUDA/OpenCL)
  - No communication/synchronization
  - No memory allocation
  - No disk IO

Flexibility

- **Variable arity** on Map and MapReduce skeletons
- **Index** argument (of current Map'd container element)
- **Uniform** arguments
- Smart container arguments accessible **freely** inside user function
  - **Read**-only / **write**-only / **read-write** copy modes
- User function **templates**

Advanced Example


```
template<typename T>
T abs(T input)
{
   return input < 0 ? -input : input;
}


template<typename T>
T mvmult(Index1D row, const Mat<T> m, const Vec<T> v)
{
   T res = 0;
   for (size_t i = 0; i < v.size; ++i)
      res += m[row.i * m.cols + i] * v[i];

   return abs(res);
}
```

Advanced/Experim. Features

- Multi-variant user function **specialization**
  - Targeting backend
- Custom **types**
- **Chained** user functions
- In-line **lambda** syntax for user functions
- "**Intrinsic**" functions
  Some functions exist in the standard library of most SkePU backends. SkePU will allow certain such functions to be called from a user function.
  Examples: sin(x), pow(x, e)

Lambda Syntax


```
auto vec_sum = Map<2>([](int a, int b)
{
   return a + b;
});

// ...

vec_sum(result, v1, v2);
```

Compilation options

Compilation

- Precompiler options
  - `skepu-tool -name` **`map_precompiled map.cpp`** `-dir` **`bin -opencl`** `-- [Clang flags]`
  - Handled by Makefiles
- Makefile.in
  - Set up your system configuration, e.g. backend compiler
- Makefile.include
  - Set up backends
- Makefile
  - Set up programs

Backend Specification

- `auto spec = skepu2::BackendSpec{skepu2::Backend::typeFromString(argv[2])};`
  - Sets the backend from a string, must match any of:
    - ”CPU”
    - ”OpenMP”
    - ”OpenCL”
    - ”CUDA”

Smart Containers

Smart Containers

- `container.updateHost();`
  - Flushes and ensures that the CPU buffer contains up-to-date values.
- `container[i] = value;`
  - Managed element access. Flushes if needed.
- `container(i) = value;`
  - Direct element access into the raw CPU buffer.

Changed in SkePU 3

Map

Map Parameter Groups

- Three groups of user function parameters:
  - **Element-wise**
    Only one element per user function call
  - **Random-access containers**
    Replicated for each memory space (e.g. GPUs)
    Proxy types Vec<T> and Mat<T> in user function
  - **Unifom scalars**
    Same values everywhere
- Argument groups are variadic (flexible count, including 0)
- Above order must be obeyed (element-wise first etc.)
- The parallelism/number of user function invocations is always determined by the return container (first argument), also in case of element-wise arity of 0.
- Also applies to **MapReduce**, **MapOverlap**!

Map – Iterators

- Optionally, use iterators with Map (and most other skeletons)
  - `mapper(r.begin(), r.end(), v1.begin(), v2.begin());`

Map Example


```
float sum(float a, float b)
{
   return a + b;
}

Vector<float> vector_sum(Vector<float> &v1, Vector<float> &v2)
{
   auto vsum = Map<2>(sum);
   Vector<float> result(v1.size());
   return vsum(result, v1, v2);
}
```

Reduce

Reduce Modes

- **1D Reduce**
  - Regular Vector
  - Matrix RowWise (returns Vector)
  - Matrix ColWise (returns Vector)

```
instance.setReduceMode(ReduceMode::RowWise) // default
```

- **”2D” Reduce**

```
instance.setReduceMode(ReduceMode::ColWise)
```

  - Regular Matrix (treated as a vector)
- `instance.setStartValue(value)`
  - Set Reduction start value. Defaults to 0-initialized.

Reduce Example


```
float min_f(float a, float b)
{
  return (a < b) ? a : b;
}

float min_element(Vector<float> &v)
{
  auto min_calc = Reduce(min_f);
  return min_calc(v);
}
```

Reduce Example


```
float plus_f(float a, float b)
{
  return a + b;
}

float max_f(float a, float b)
{
  return (a > b) ? a : b;
}

auto max_sum = skepu2::Reduce(plus_f, max_f);

max_sum.setReduceMode(skepu2::ReduceMode::RowWise);
r = max_sum(m);
```

MapReduce

MapReduce

- `instance.setDefaultSize(size_t)`
  - When the element-wise arity is 0, this controls the number of user function invocations
    (That is, the size of the ”virtual” temporary container in between the Map and Reduce steps)
- `instance.setStartValue(value)`
  - Set Reduction start value. Defaults to 0-initialized.

MapReduce Example

```
float add(float a, float b)
{
   return a + b;
}

float mult(float a, float b)
{
   return a * b;
}

float dot_product(Vector<float> &v1, Vector<float> &v2)
{
   auto dotprod = MapReduce<2>(mult, add);
   return dotprod(v1, v2);
}
```

Scan

Scan

- `instance.setScanMode(mode)`
  - Set the scan mode:
    `ScanMode::Inclusive (default)`
    `ScanMode::Exclusive`
- `instance.setStartValue(value)`
  - Set start value of scans. Defaults to 0-initialized.

Scan Example

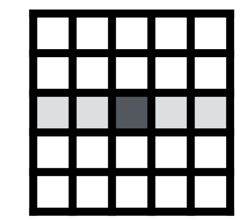

```
float max_f(float a, float b)
{
  return (a > b) ? a : b;
}

Vector<float> partial_max(Vector<float> &v)
{
  auto premax = Scan(max_f);
  Vector<float> result(v.size());
  return premax(result, v);
}
```

MapOverlap

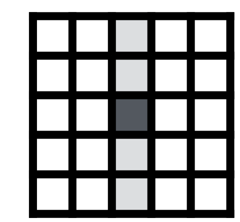
MapOverlap Modes

- **1D MapOverlap** `With 1D user function`
  - Regular Vector

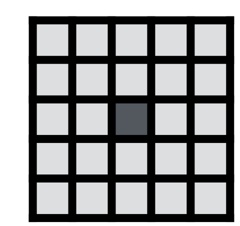
  - Matrix RowWise `instance.setOverlapMode(Overlap::RowWise) // default`



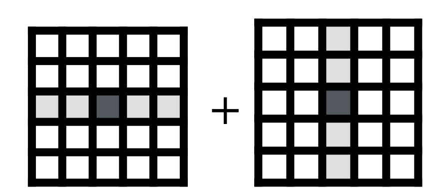
  - Matrix ColWise `instance.setOverlapMode(Overlap::ColWise)`



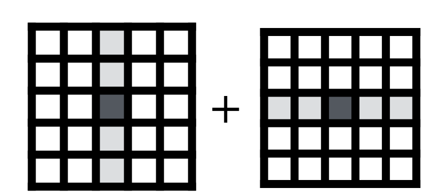
- **2D MapOverlap**
  - Regular Matrix



- **Separable MapOverlap (2D-with-1D)**
  - Matrix RolColWise `instance.setOverlapMode(Overlap::RowColWise)`



  - Matrix ColRowWise `instance.setOverlapMode(Overlap::ColRowWise)`



MapOverlap Edge Mode

- `instance.setOverlap(x, [y])`
  - Set overlap radius
- `instance.setEdgeMode(mode)`
  - Edge::Pad
    - `instance.setPad(pad)` – set value
  - Edge::Duplicate (default)
  - Edge::Cyclic

MapOverlap 1D Example


```
float conv(
   int overlap, size_t stride,
   const float *v, const Mat<float> stencil, float scale
)
{
   float res = 0;
   for (int i = -overlap; i <= overlap; ++i)
      res += stencil[i + overlap] * v[i*stride];
   return res / scale;
}

Vector<float> convolution(Vector<float> &v)
{
   auto convol = MapOverlap(conv);
   Vector<float> stencil {1, 2, 4, 2, 1};
   Vector<float> result(v.size());
   convol.setOverlap(2);
   return convol(result, v, stencil, 10);
}
```

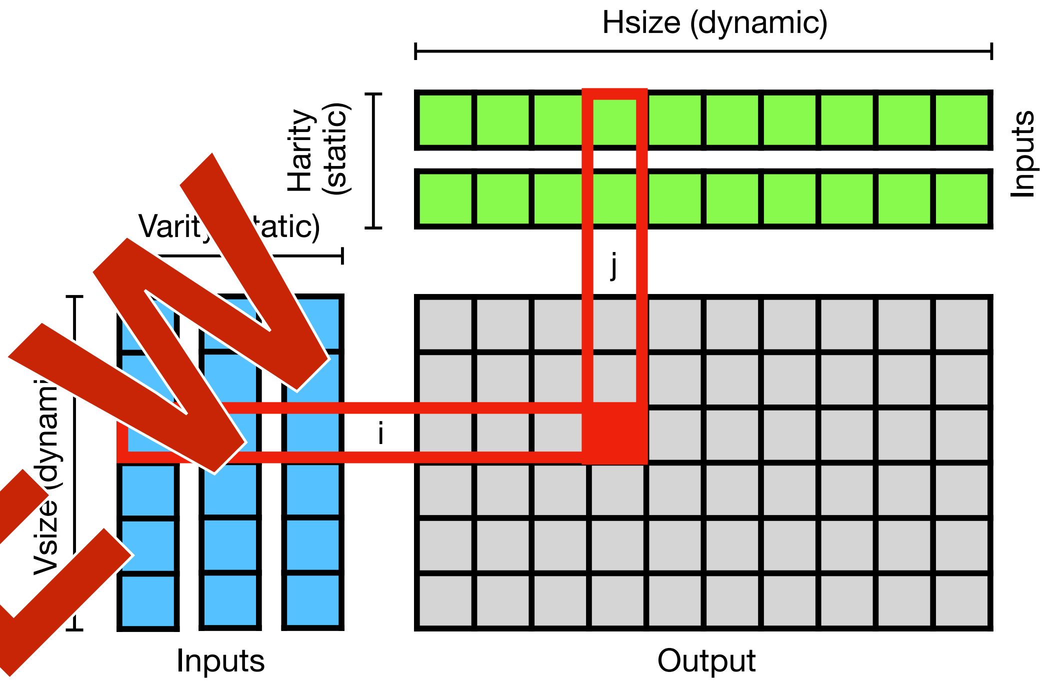
MapOverlap 2D Example


```
float over_2d(
    int ox, int oy, size_t stride, const float *m,
    const skepu2::Mat<float> filter
)
{
   float res = 0;
   for (int y = -oy; y <= oy; ++y)
      for (int x = -ox; x <= ox; ++x)
         res += m[y*(int)stride+x]
                  * filter.data[(y+oy)*ox + (x+ox)];
   return res;
}
```

SkePU 3 preview

SkePU 3 preview

- New skeleton
  - **MapPairs**
- Higher-dimensionality containers
  - **Tensor3<T>, Tensor4<T>**
- Multiple return values from user functions
  - Can already return by struct: *array-of-records* format
  - New feature allows result in multiple *separate* arrays
- Improved MapOverlap user-function syntax
- And more to come!



MapPairs


```
int uf(int a, int b) { return a * b; }

// …

auto pairs = skepu::MapPairs<1, 1>(uf);

skepu::Vector<int> v1(Vsize, 3), h1(Hsize, 7);

skepu::Matrix<int> res(Vsize, Hsize);

pairs(res, v1, h1);
```

MapOverlap

```
float over_1d(skepu::Region1D<float> r, int scale)
{
   return (r(-2)*4 + r(-1)*2 + r(0) + r(1)*2 + r(2)*4) / scale;
}



float over_2d(skepu::Region2D<float> r, const skepu::Mat<float> stencil)
{
   float res = 0;
   for (int i = -r.oi; i <= r.oi; ++i)
      for (int j = -r.oj; j <= r.oj; ++j)
         res += r(i, j) * stencil(i + r.oi, j + r.oj);
   return res;
}
```

SkePU

DEMO

SkePU in
Current Research

SkePU in **Teaching**