GraphIt to CUDA compiler in 2021 LOC: A case for high-performance DSL implementation via staging with **BuilDSL**

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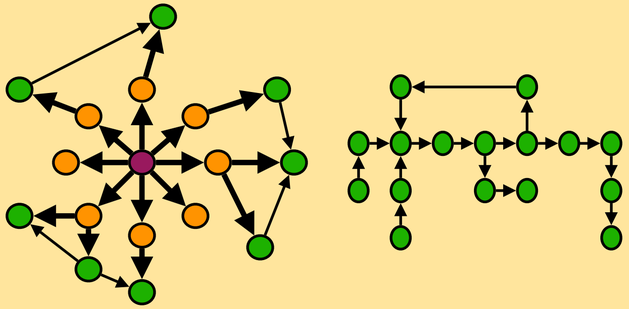
DSLs enable high-performance

- Performance critical domains require *domain-specific* optimizations

DSLs enable high-performance



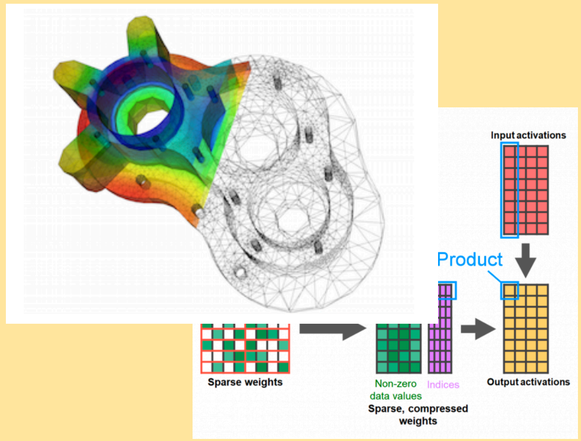
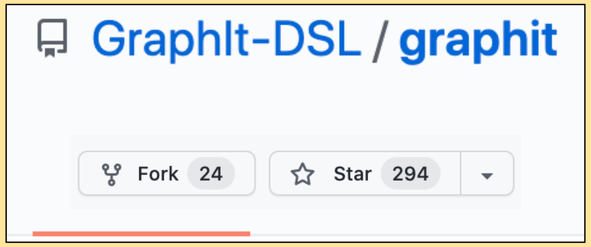
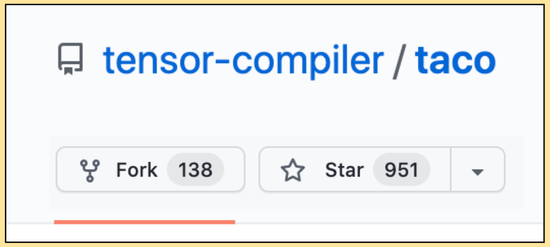


Image Processing **Graph Processing** **Sparse Array Processing**





- Built **for** domain-experts *with* domain-experts!

DSLs enable high-performance

- Built **for** domain-experts *with* domain-experts!

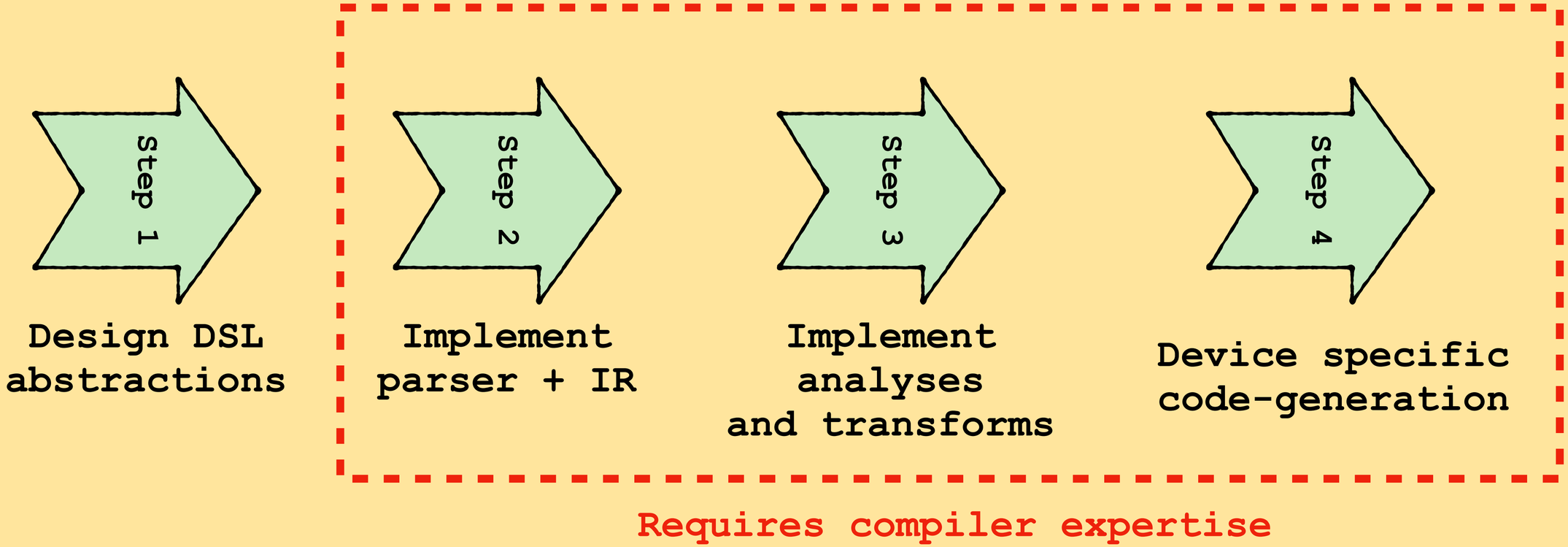
- Built **for** domain-experts **by** domain-experts!

BuildIt!

1. Ajay Brahmakshatriya and Saman Amarasinghe. 2021. BuildIt: a type-based multi-stage programming framework for code generation in C++. Proc. CGO 2021

Writing DSLs is hard

Typical DSL development cycle

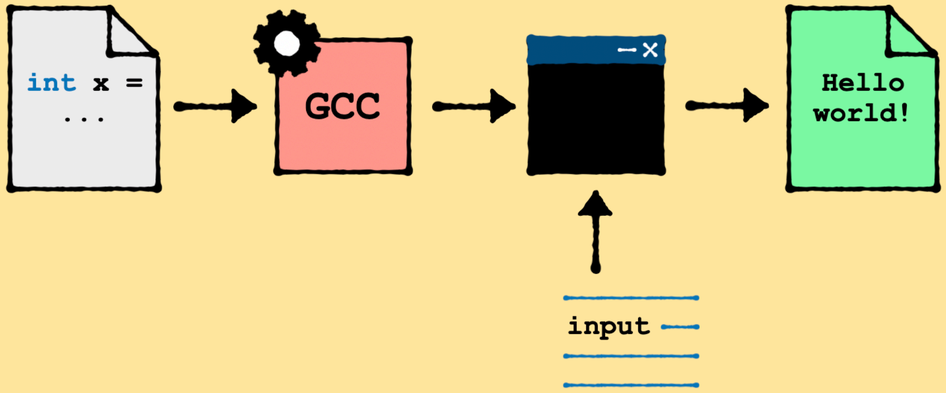


- Domain experts can and do write high-performance libraries

BuildIt

Multi-stage programming in C++

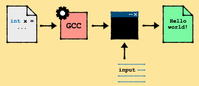
- BuildIt brings multi-stage programming to C++ in a lightweight way

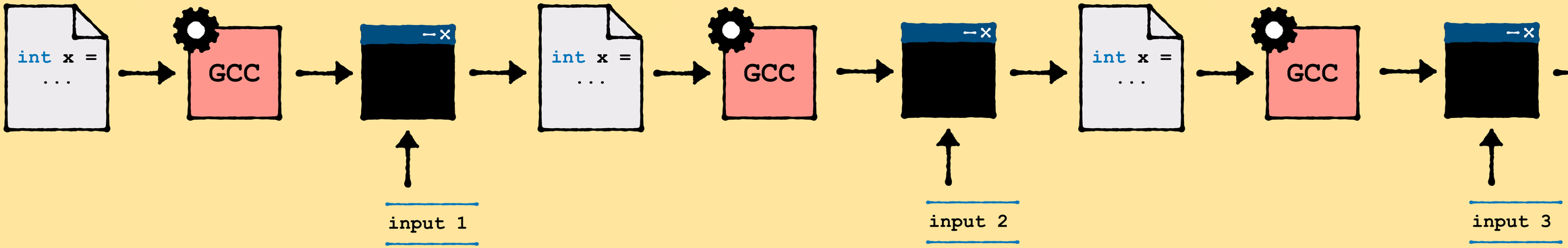


BuildIt

Multi-stage programming in C++

- BuildIt brings multi-stage programming to C++ in a lightweight way





BuildIt

Multi-stage programming in C++

- BuildIt uses types to differentiate stages/binding times

dyn_var<**T**> static_var<**T**>

BuildIt

Multi-stage programming in C++

- BuildIt uses types to differentiate stages/binding times

static_var<**T**>

dyn_var<**T**>

Evaluation of expressions of type dyn_var<T> is delayed to next stage

```
dyn<int> x = 0;
dyn<float> y = 3.14f;

x = y + 2.71f;

if (x > 8.0f)
    y = 0;
else
    y = 1;
```

```
int x = 0;
float = 3.14f;

x = y + 2.71f;

if (x > 8.0f)
    y = 0;
else
    y = 1;
```

BuildIt

Multi-stage programming in C++

- BuildIt uses types to differentiate stages/binding times

dyn_var<**T**>

static_var<**T**>

static_var<T> is completely evaluated in the current stage

```
static<int> x = 0;

dyn<float> y = 0.0f;

y = y + x;

if (x > 1)
    y = 0;
else
    y = 1;
```

```
float = 3.14f;

y = y + 0; // x = 0


// no condition on x

y = 1;
```

BuildIt

Specialization with static_var(s)

```
dyn_var<int> power_f(dyn_var<int> base,
     static_var<int> exponent) {

  dyn_var<int> res = 1, x = base;

  while (exponent > 1) {
    if (exponent % 2 == 1)
      res = res * x;
    x = x * x;
    exponent = exponent / 2;
  }
  return res * x;
}
```

```
int power_5 (int arg0) {
  int var0 = arg0;
  int var1 = 1;
  int var2 = var0;
  var1 = var1 * var2;
  var2 = var2 * var2;
  var2 = var2 * var2;
  int var3 = var1 * var2;
  return var3;
}
```

```
exponent = 5
```

BuildIt

Specialization with static_var(s)

```
dyn_var<int> power_f(dyn_var<int> base,
     static_var<int> exponent) {

  dyn_var<int> res = 1, x = base;

  while (exponent > 1) {
    if (exponent % 2 == 1)
      res = res * x;
    x = x * x;
    exponent = exponent / 2;
  }
  return res * x;
}
```

```
int power_10 (int arg0) {
  int var0 = arg0;
  int var1 = 1;
  int var2 = var0;
  var2 = var2 * var2;
  var1 = var1 * var2;
  var2 = var2 * var2;
  var2 = var2 * var2;
  int var3 = var1 * var2;
  return var3;
}
```

```
exponent = 10
```

BuildIt

Specialization with static_var(s)

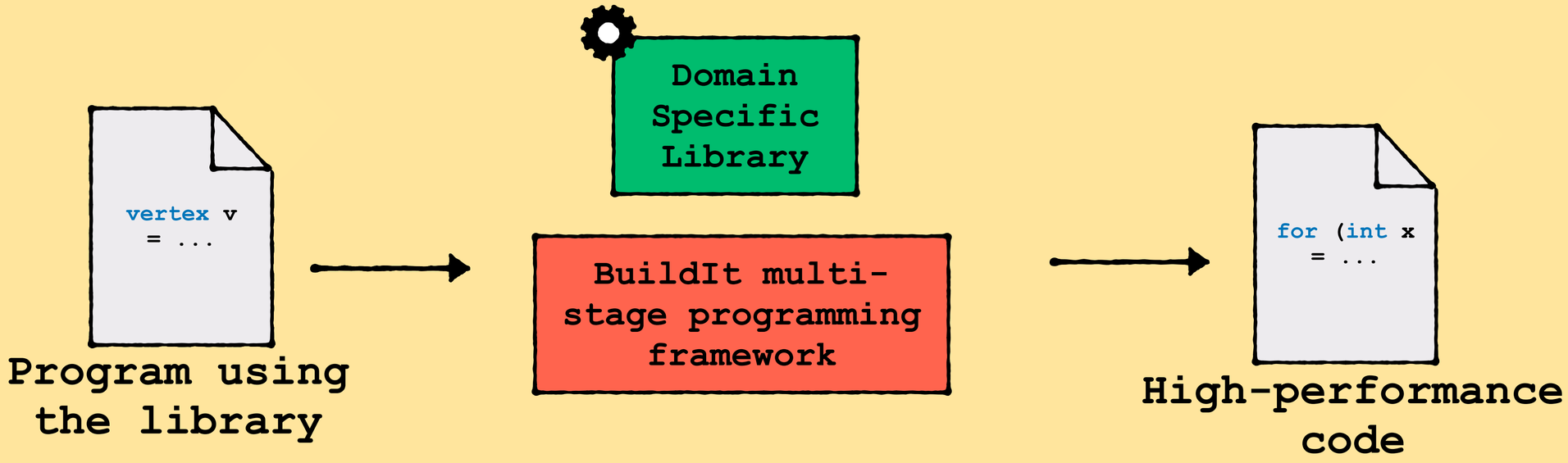
```
dyn_var<int> power_f(dyn_var<int> base,
     static_var<int> exponent) {

  dyn_var<int> res = 1, x = base;

  while (exponent > 1) {
    if (exponent % 2 == 1)
      res = res * x;
    x = x * x;
    exponent = exponent / 2;
  }
  return res * x;
}
```

```
int power_15 (int arg0) {
  int var0 = arg0;
  int var1 = 1;
  int var2 = var0;
  var1 = var1 * var2;
  var2 = var2 * var2;
  var1 = var1 * var2;
  var2 = var2 * var2;
  var1 = var1 * var2;
  var2 = var2 * var2;
  int var3 = var1 * var2;
  return var3;
}
```

```
exponent = 15
```

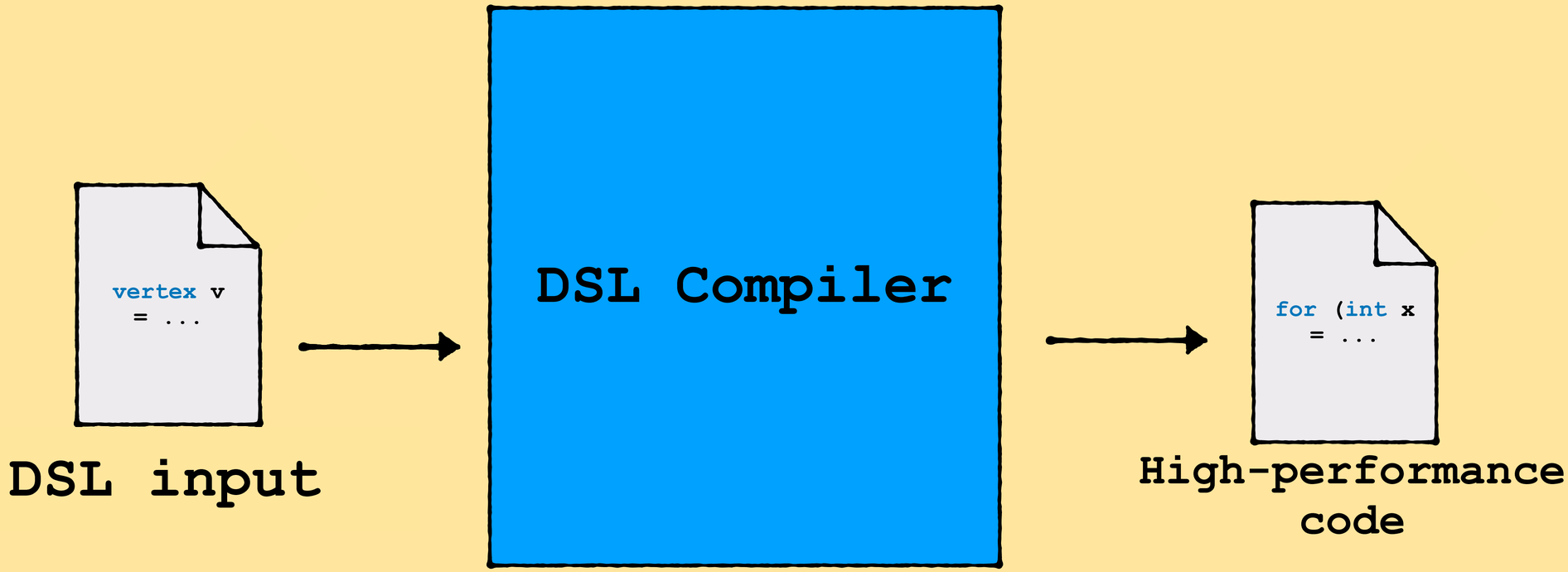
Staging libraries with BuildIt

A simple intuition



Staging libraries with BuildIt

A simple intuition



Domain Specific Analysis?

Domain Specific Transformations?

Scheduling?

Device specific CPU/GPU/… code generation?

Building a DSL demo

Language for Einsum expressions

- Implement a DSL for Einsum expressions

```
A[j] = B[j][k] * C[k]
```

- Scheduling and parallelize for CPUs and GPUs

- Implement constant propagation analysis + transformation

Building a DSL demo

Language for Einsum expressions

$$A[j] = B[j][k] * C[k]$$

shorthand for

$$\forall\ j,\ A[j] = \sum_{k=0}^{N} B[j][k] * C[k]$$

- Implement loop nests for LHS and RHS
- Implement sum reduction

Building a DSL demo

Language for Einsum expressions

$$\forall\ j,\ A[j] = \sum_{k=0}^{N} B[j][k] * C[k]$$

```
struct Tensor {
  float * data; std::vector<int> dims;
  operator = (T rhs_expr) {
    if (this->rank == 1) {
      for (int i = 0; i < this->dims[0]; i++) {
        data[i] = evaluate_rhs(rhs_expr, i);
      }
    } else if (this->rank == 2) {
      for (int i = 0; i < this->dims[0]; i++) {
        for (int j = 0; j < this->this[1]; j++) {
          data[I * dim[0] + j] = evaluate_rhs(rhs_expr, i, j);
        }
      }
    } else if
       ...
  }
};
```

Building a DSL demo

Language for Einsum expressions

$$\forall\ j,\ A[j] = \sum_{k=0}^{N} B[j][k] * C[k]$$

```
struct Tensor {
  float * data; std::vector<int> dims;

  void recursive_loop(int idx, int offset, T rhs) {
    if (idx < dims.size()) {
      for (int i = 0; i < dims[idx]; i++) {
          recursive_loop(idx + 1, offset + …, rhs(i));
      }
    } else {
        data[offset] = rhs;
    }
  }

  operator = (T rhs_expr) {
      recursive_loop(0, rhs_expr);
  }

};
```

Building a DSL demo

Language for Einsum expressions

$$\forall\ j,\ A[j] = \sum_{k=0}^{N} B[j][k] * C[k]$$

```
struct Tensor {
  float * data; std::vector<int> dims;

  void recursive_loop(int idx, int offset, T rhs) {
    if (idx < dims.size()) {
      for (int i = 0; i < dims[idx]; i++) {
        recursive_loop(idx + 1, offset * dims[idx] + i, rhs);
      }
    } else {
        data[offset] = rhs;
    }
  }

  operator = (T rhs_expr) {
      recursive_loop(0, rhs_expr);
  }

};
```

Same approach for recursively iterating over RHS free variables!

Building a DSL demo

Source code

Demo source code

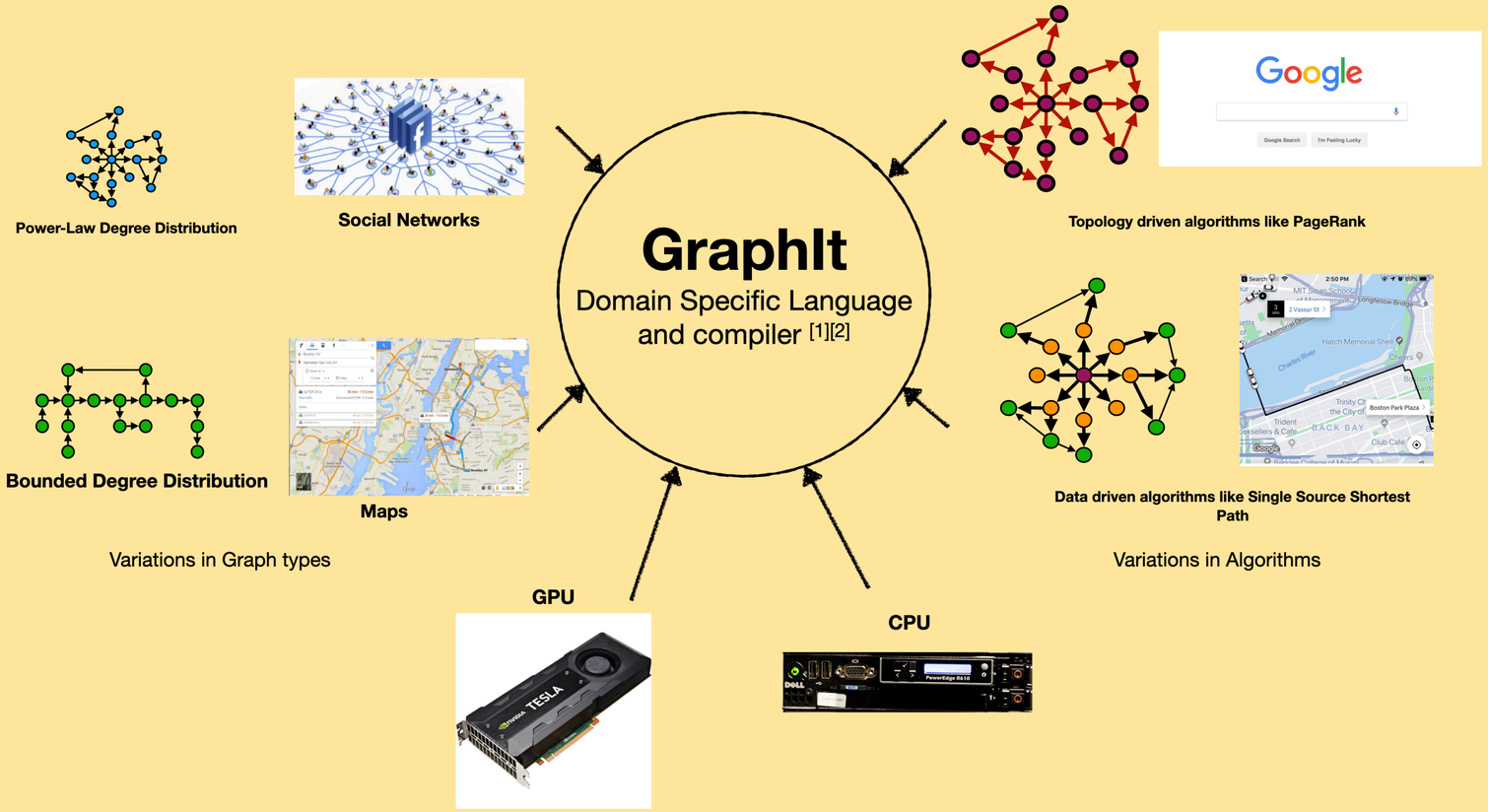
https://github.com/BuildIt-lang/einsum-lang

BuildIt

https://buildit.so

GraphIt DSL

- A real world state of the art graph DSL

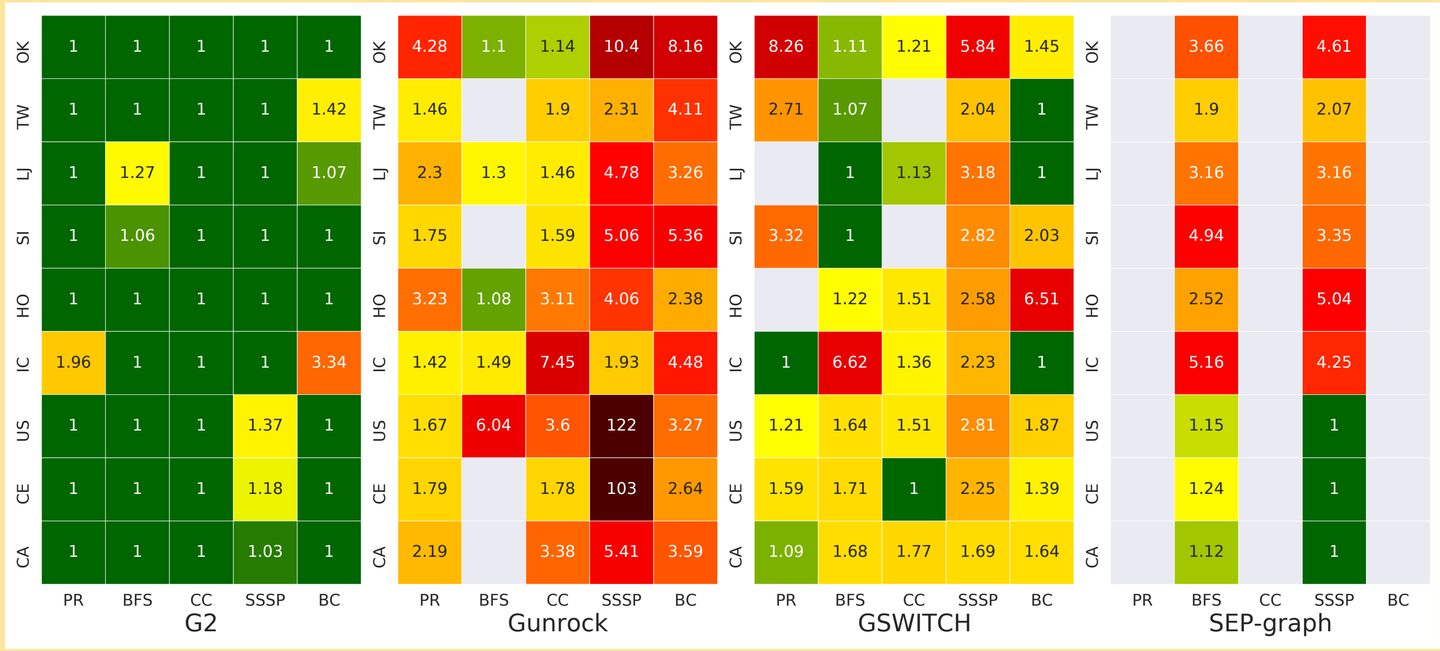


1. Zhang et.al. , GraphIt: a high-performance graph DSL. Proc. ACM Program. Lang. 2, OOPSLA, Article 121 (November 2018)
2. Brahmakshatriya et.al. , Compiling Graph Algorithms for GPUs with GraphIt. International Symposium on Code Generation and Optimization (CGO 2021)

GraphIt DSL on GPUs

State of the art performance

Optimization	Gunrock	GSWITCH	SEP-Graph	G2
Load Balancing	VERTEX BASED, EDGE BASED, TWC	CM, WM, TWC, STRICT	VERTEX BASED	ETWC, TWC, STRICT, CM, WM, VERTEX BASED, EDGE BASED
Edge Blocking	Not supported	Not supported	Not supported	Supported
Vertex Set Creation	Fused/Unfused	Fused/Unfused	Fused	Sparse Queue/ Bitmap/Boomlet
Direction Optimization	Push/Pull/Hybrid	Push/Pull/Hybrid	Push/Pull/Hybrid	Push/Pull/Hybrid
Deduplication	Supported	Not supported	Supported	Supported
Vertex Ordering	Supported	Supported	Supported	Supported
Kernel Fusion	Supported	Not supported	Supported	Supported
Total combinations	48	32	16	**576**



Largest Scheduling Space

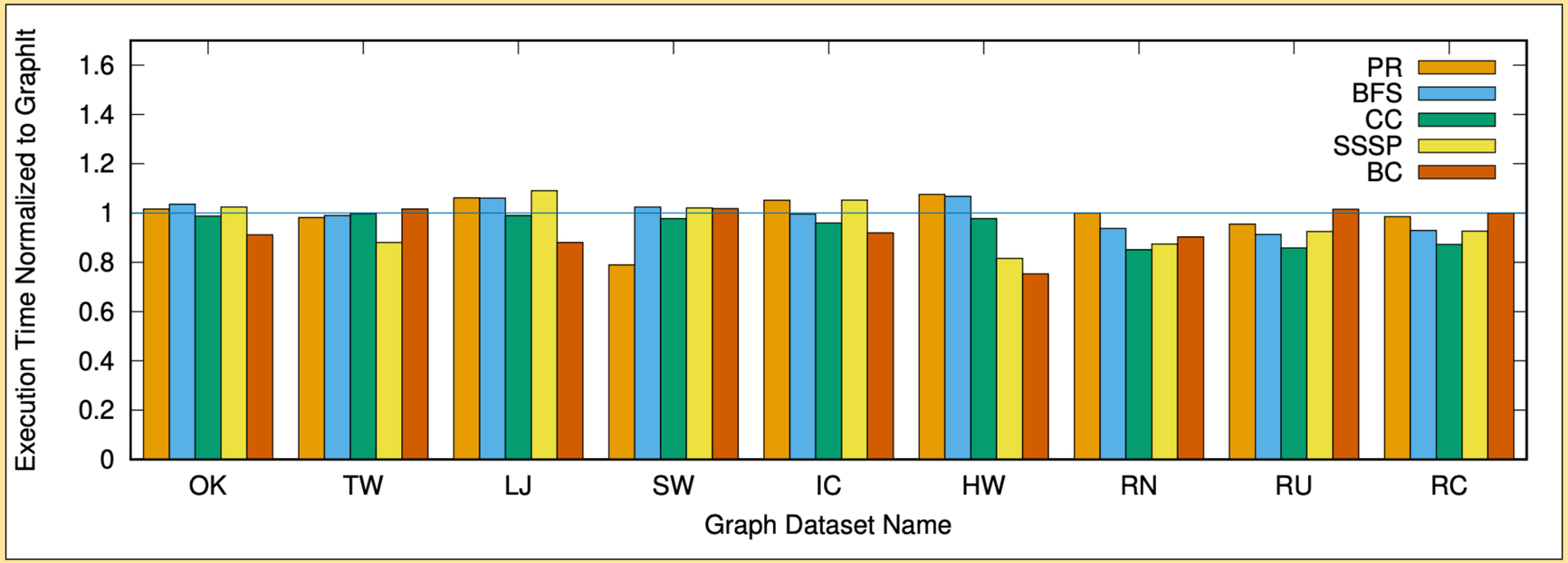
State of the art performance

23,783 lines of compiler code!!!

GraphIt DSL with BuildIt

```
GraphT g = ...;
builder::annotate("CUDA_KERNEL");
for (dyn<int> cta = 0; cta < 60; cta = cta + 1) {
  for (dyn<int> t = 0; t < 512; t = t + 1) {
    dyn<int> tid = cta * 512 + t;
    dyn<int> edge_dst = g.edges[tid];
    ...
  }
}
```

BuildIt annotations for GPU code




```
struct Vertex {
    dyn_var<int> vid;

    // Data flow analysis with static values
    static_var<int> shared;

    operator + (…) {
    }
};
```

Dataflow analysis to insert atomics

Obtain comparable performance with GraphIt compiler for 45 experiments

In just 2021 lines of code on top of BuildIt!

```
SimpleGPUSchedule s1;
s1.configDirection(direction_type::PULL, frontier_rep::BITMAP);
s1.configLoadBalance(load_balance::VERTEX_BASED);
s1.configFrontierCreation(frontier_rep::BITMAP);
edgeset_apply(s1).from(frontier).apply_modified(...);
```

Support generating all 576 combinations of schedules

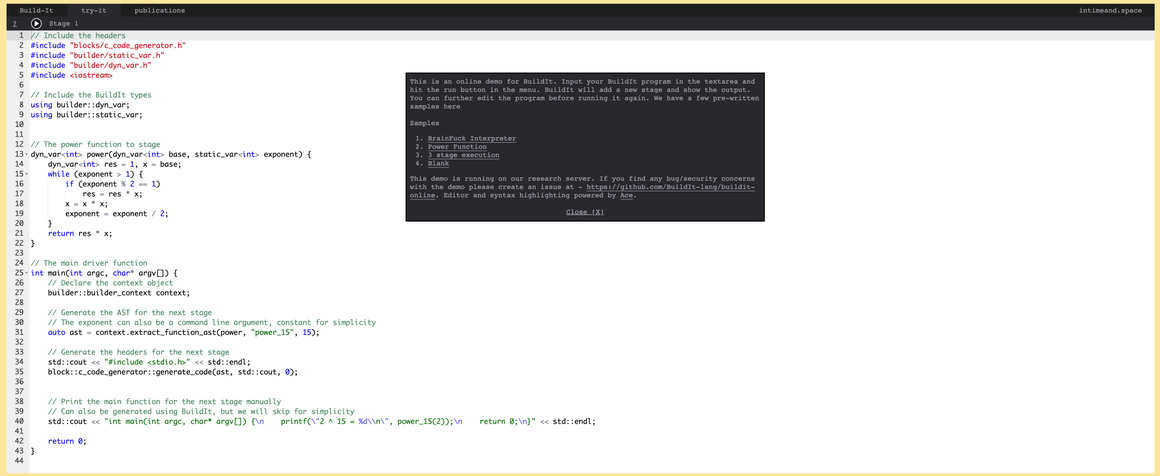

```
// Specialization based on current context
if (current_context == HOST) {
  current_context = DEVICE;
  builder::annotate("CUDA_KERNEL");
  for (dyn<int> ct = 0; ct < MAX_CTA; ct = ct + 1) {
    for (dyn<int> t = 0; t < MAX_T; t = t + 1) {
      dyn<int> tid = ct * MAX_T + t;
      ...
    }
  }
  current_context = HOST;
} else {
  dyn<int> ct   = *cta_ptr;
  dyn<int> t    = *t_ptr;
  dyn<int> tid  = ct * MAX_T + t;
  ...
  // Synchronize the grid to ensure correctness
  grid_sync();
}
```

Fusing multiple operators into single kernel to avoid launch overheads

BuildIt

Write high-performance DSLs with ease

BuildIt is available open source under the MIT license at **https://buildit.so**



Try Online: buildit.so/tryit/

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