Automated GPU Kernel Fusion with XLA

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Presenting work done by the XLA team

Outline

- TensorFlow
- Kernel fusion
- XLA compiler
- Automated kernel fusion

TensorBoard

EVENTS IMAGES GRAPH HISTOGRAMS

Fit to screen

Run cifar-train

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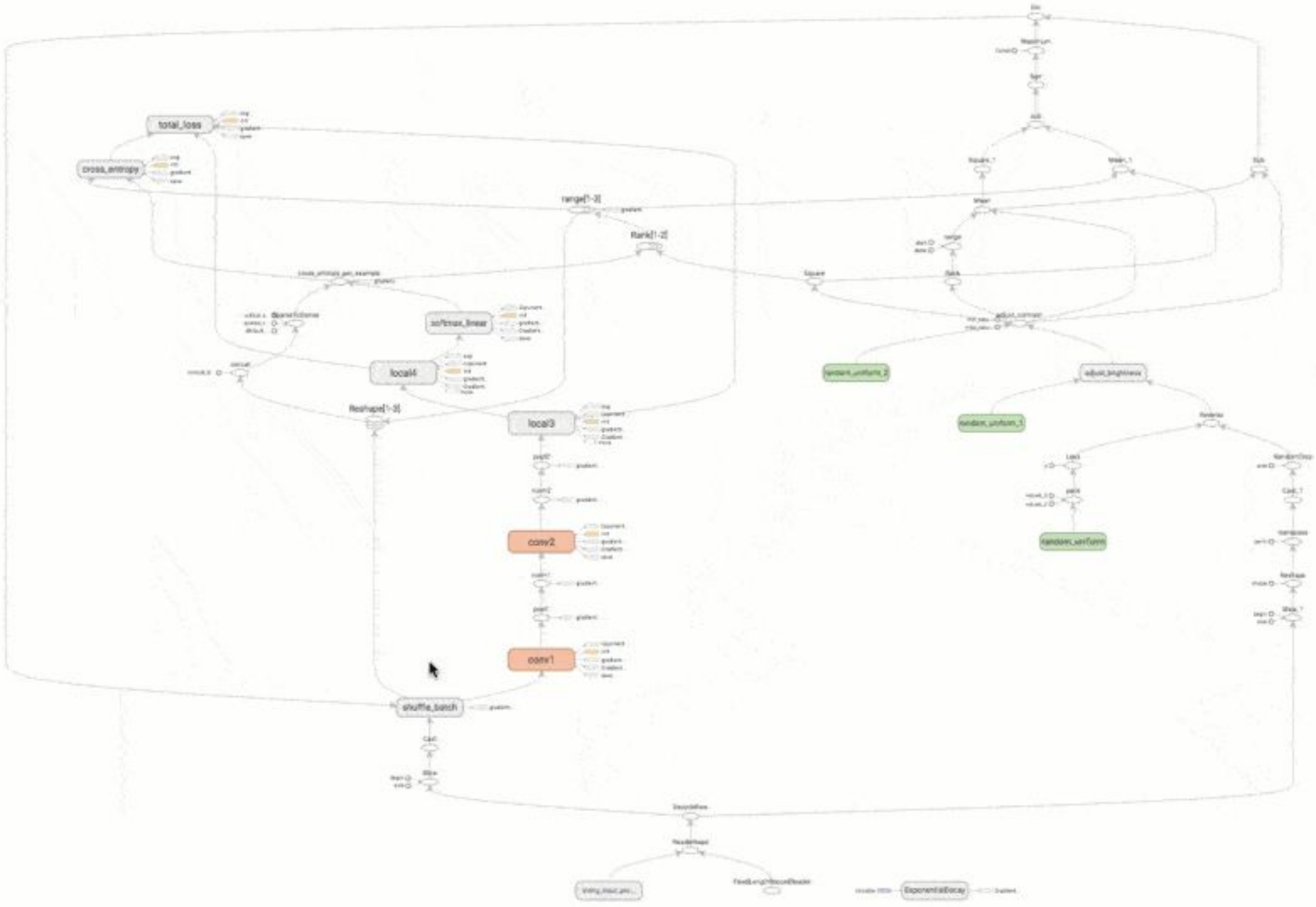
Color Structure

color: same substructure
gray: unique substructure

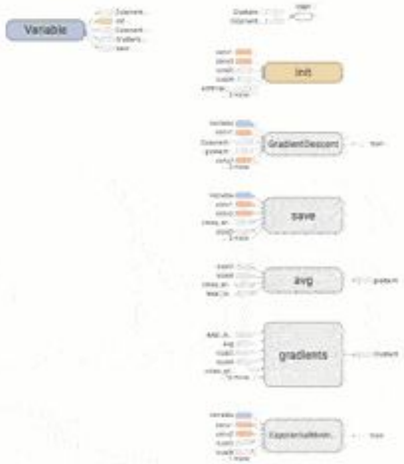
Graph (* = expandable)

- Namespace*
- OpNode
- Unconnected series*
- Connected series*
- Constant
- Summary
- Dataflow edge
- Control dependency edge
- Reference edge

Main Graph

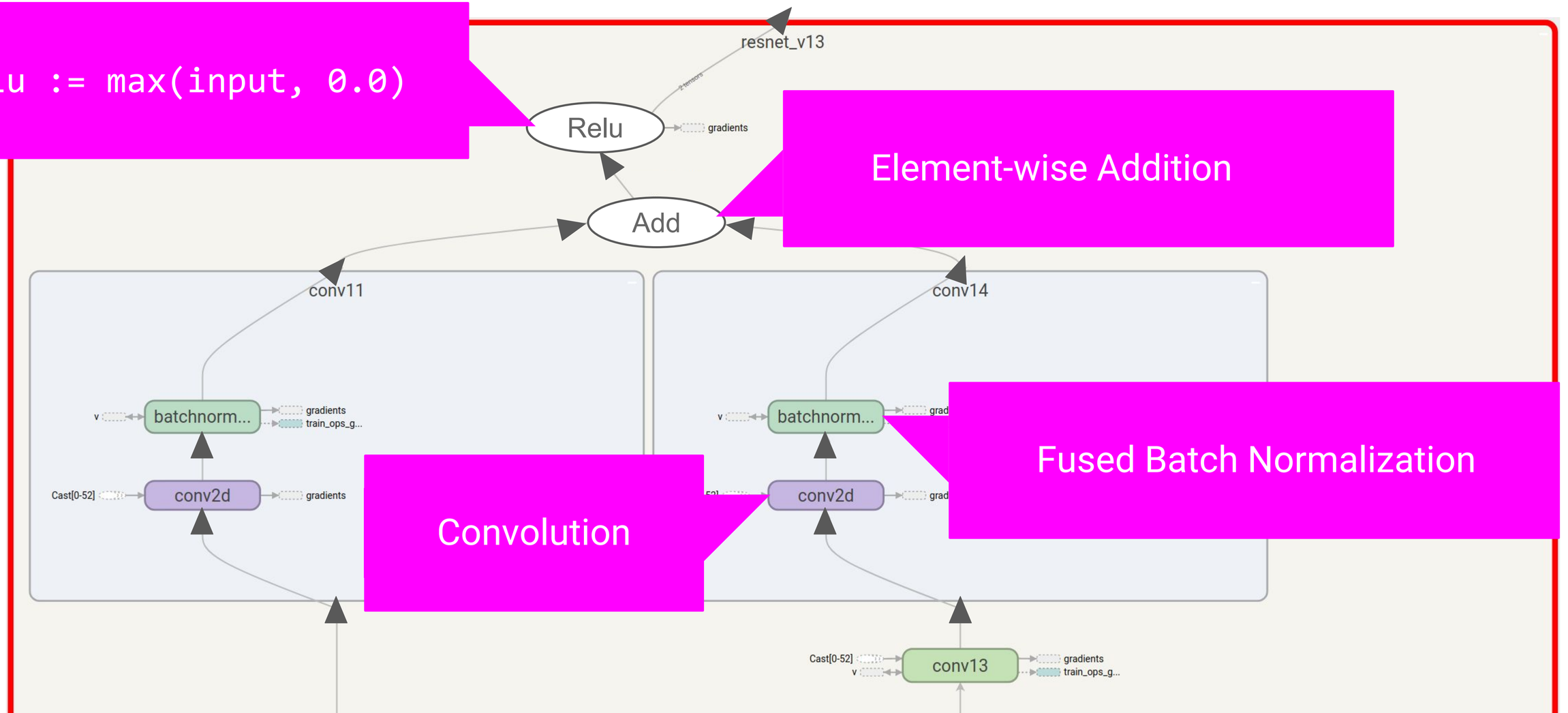


Auxiliary nodes



Example: ResNet block

```
ReLu := max(input, 0.0)
```



Fused Kernels

- Convenient
- Performant

```
// Compute a * x + y.
// a is a scalar, x and y are tensors.
tmp = tf.multiply(a, x)
out = tf.add(tmp, y)
```

```
// Compute a * x + y.
// a is a scalar, x and y are tensors.
tmp = tf.multiply(a, x)
out = tf.add(tmp, y)

__global__ void Multiply(int n, float a, float* x) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) x[i] = a * x[i];
}
```

```
// Compute a * x + y.
// a is a scalar, x and y are tensors.
tmp = tf.multiply(a, x)
out = tf.add(tmp, y)
```

Tensors read + written: 4

```
__global__ void Multiply(int n, float a, float* x) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) x[i] = a * x[i];
}
__global__ void Add(int n, float* x, float* y) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) x[i] = x[i] + y[i];
}
```

```
// Compute a * x + y.
// a is a scalar, x and y are tensors.
tmp = tf.multiply(a, x)
out = tf.add(tmp, y)

__global__ void FusedMulAdd(int n, float a, float* x, float* y) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) x[i] = a * x[i] + y[i];
}
```

```
// Compute a * x + y.
// a is a scalar, x and y are tensors.
out = tf.fused_multiply_add(a, x, y)
```

Tensors read + written: 3

25% reduction!

```
__global__ void FusedMulAdd(int n, float a, float* x, float* y) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) x[i] = a * x[i] + y[i];
}
```

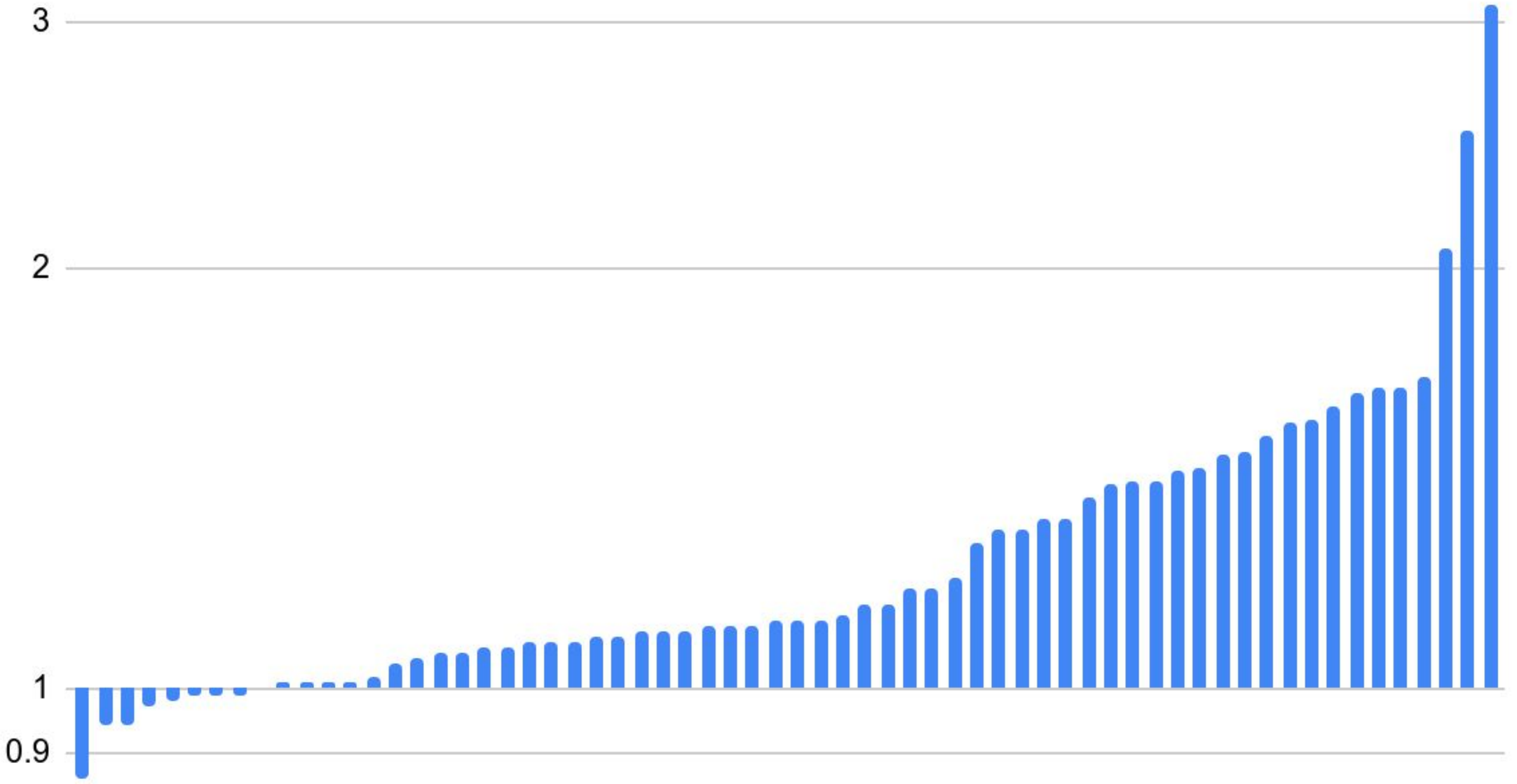
Fused Kernels

- Convenient
- Performant

But

- Development cost
- Inflexibel
- Hard to optimize

Speedup of TF with XLA vs TF without XLA

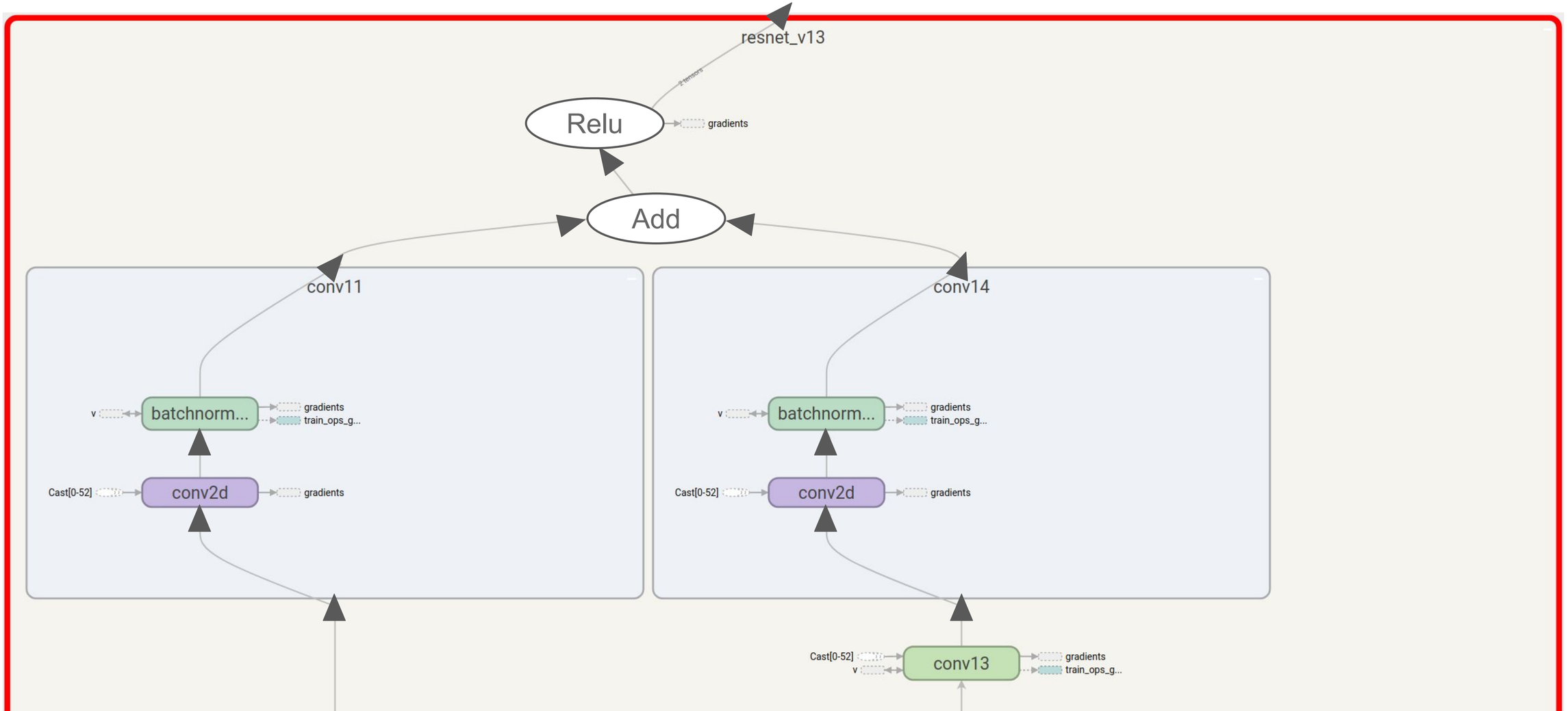


Submitter	Hardware	Chip count	Software	ResNet-50 v1.5 *
NVIDIA	DGX-1 (on premise)	8	ngc18.11_MXNet, cuDNN 7.4	65.6
Google	8x Volta V100 (Cloud)	8	TF 1.12, cuDNN 7.4	64.1

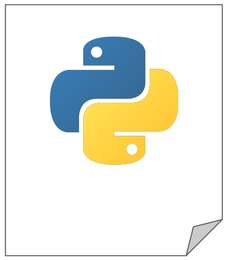
Full results: https://mlperf.org/results/

* speedup relative to reference implementation

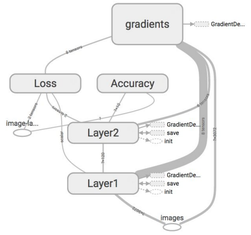
Example: ResNet block



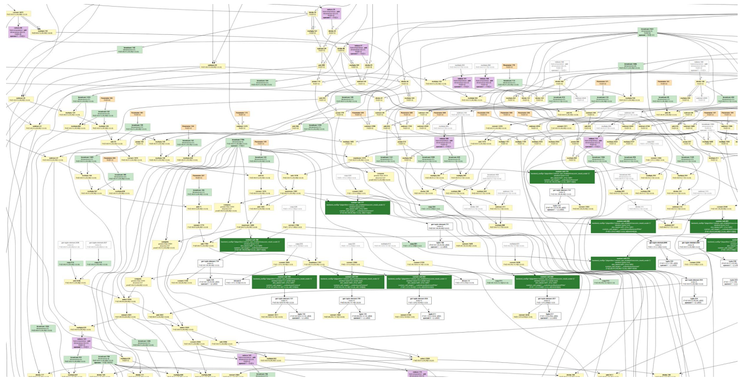
TensorFlow with XLA



TensorFlow Model



TensorFlow Graph



XLA Intermediate Representation: HLO

HLO Fusion happens here!

XLA target-independent & target-specific optimizations

TPU

GPU

CPU

Target-specific code generation

HLO IR

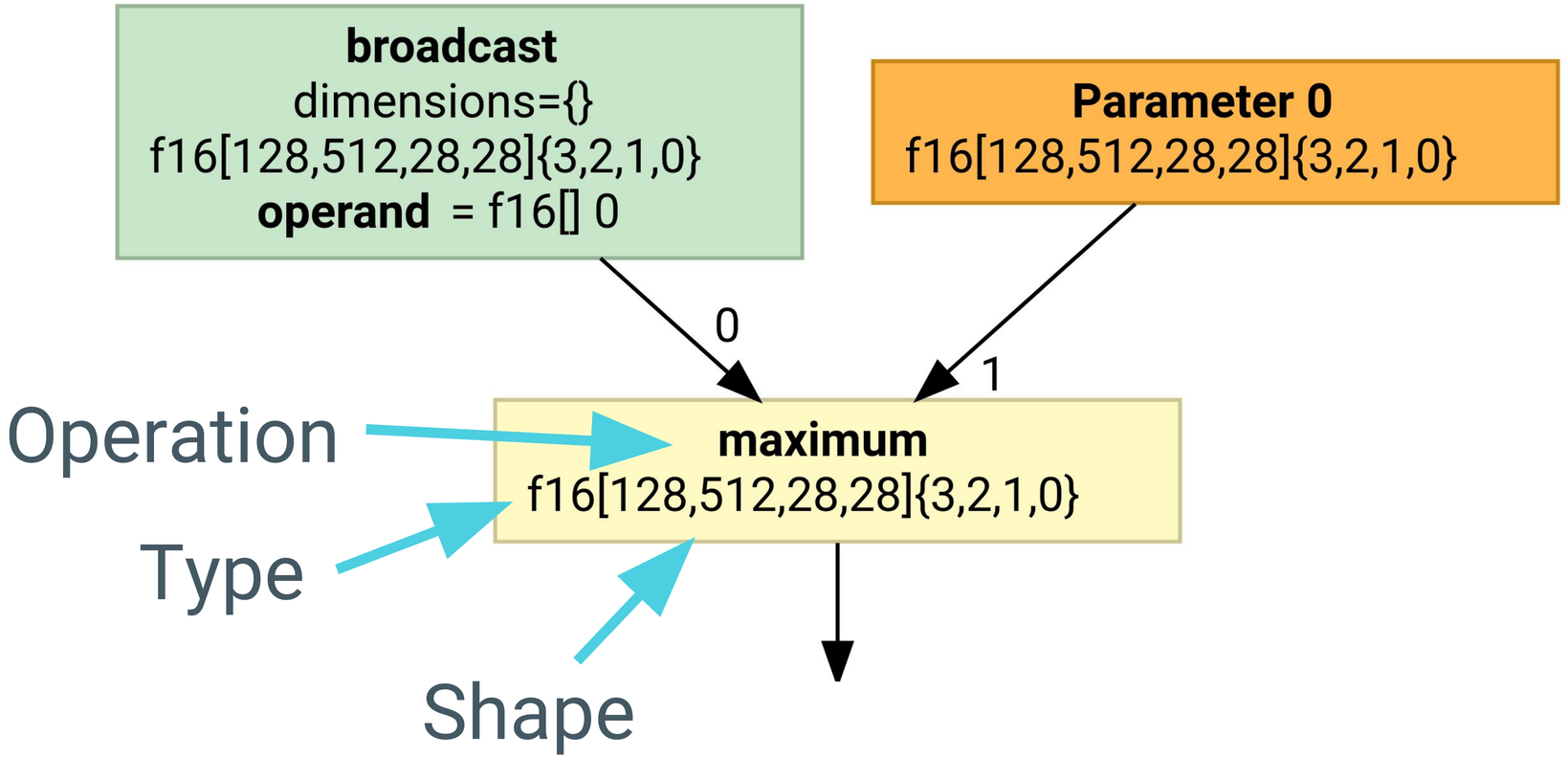
Sample HLO ops

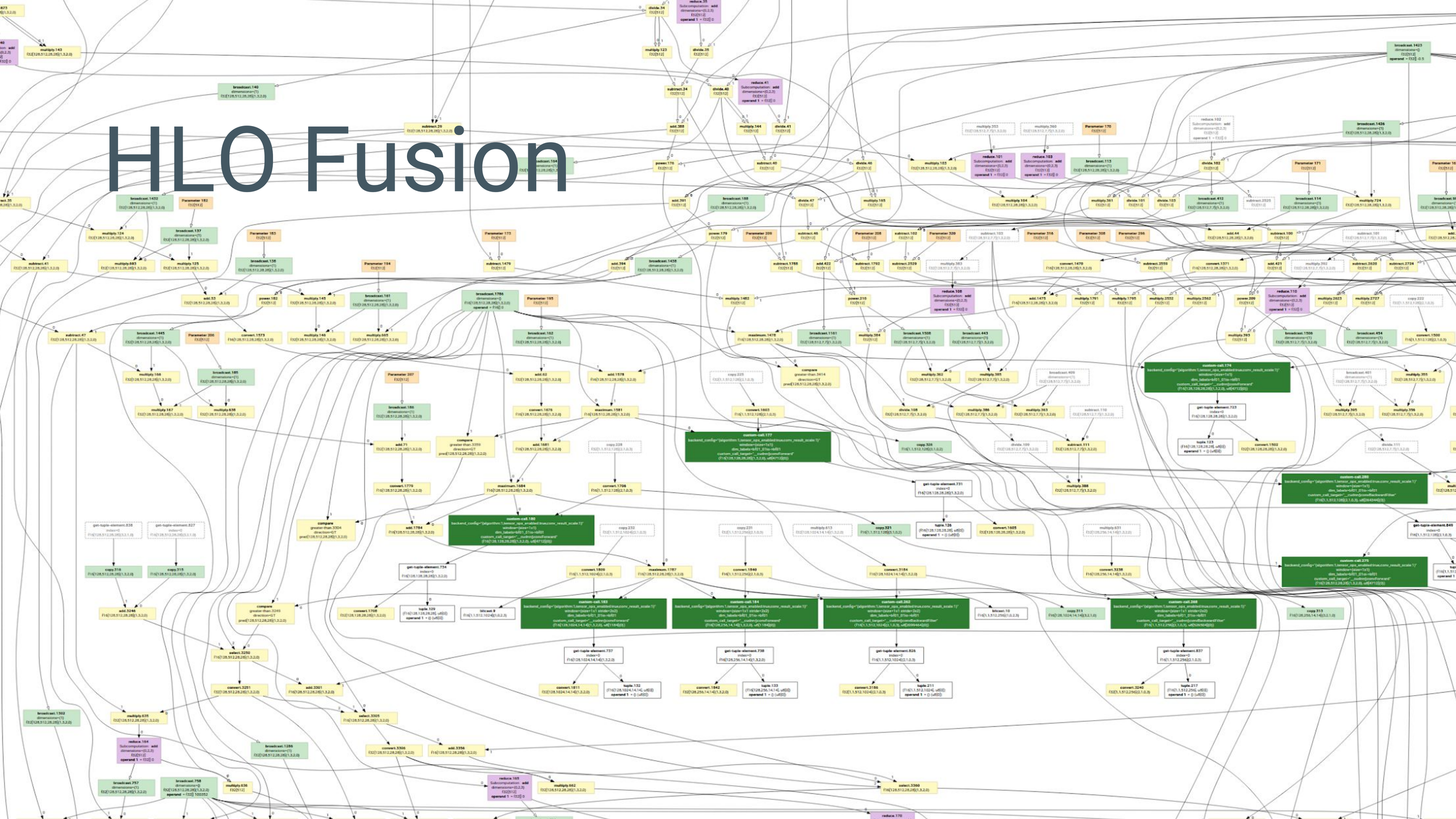
- Elementwise math
  - Add, Tanh, Map
- Spezialized math for neural nets
  - Dot, Convolution, Reduce
- Re-organize data
  - Reshape, Broadcast, Concat, Tuple
- Control flow
  - While, Call, CustomCall
- Data transfer
  - Parameter, Constant

Sample data types

- Primitive types
  - PRED
  - F16
  - F32
- Composite types
  - array: F32[2,3], F16[]
  - tuple: TUPLE(F32[16], F16)

ReLu in HLO


broadcast
dimensions={}
f16[128,512,28,28]{3,2,1,0}
operand = f16[] 0
Parameter 0
f16[128,512,28,28]{3,2,1,0}
0
1
maximum
f16[128,512,28,28]{3,2,1,0}
Operation
Type
Shape

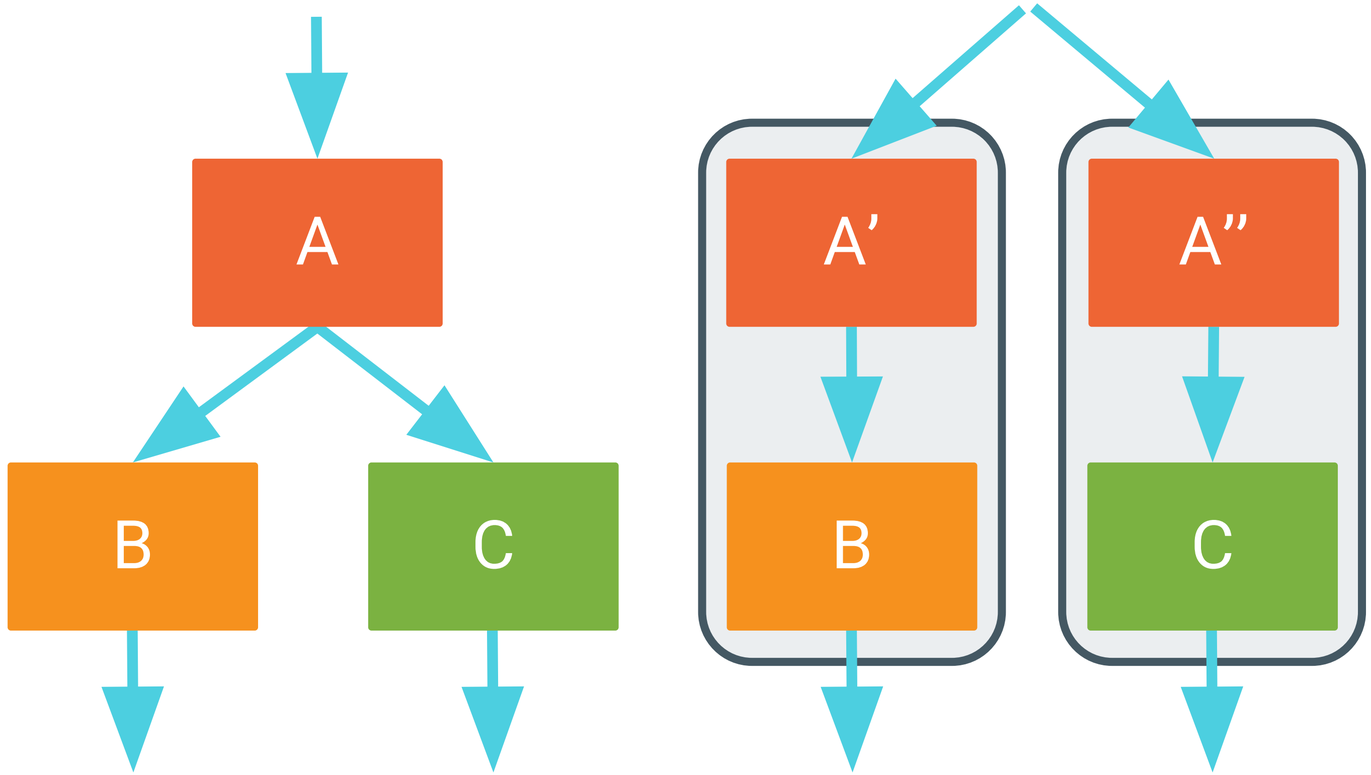

HLO Fusion

HLO Fusion

- Reduce memory bandwidth
- Compatible loop pattern
- Coalesced memory access

HLO Fusion

1) Fusion (with duplication)
2) Sibling fusion
3) Fusion with multiple outputs



HLO Fusion

1) Fusion (with duplication)
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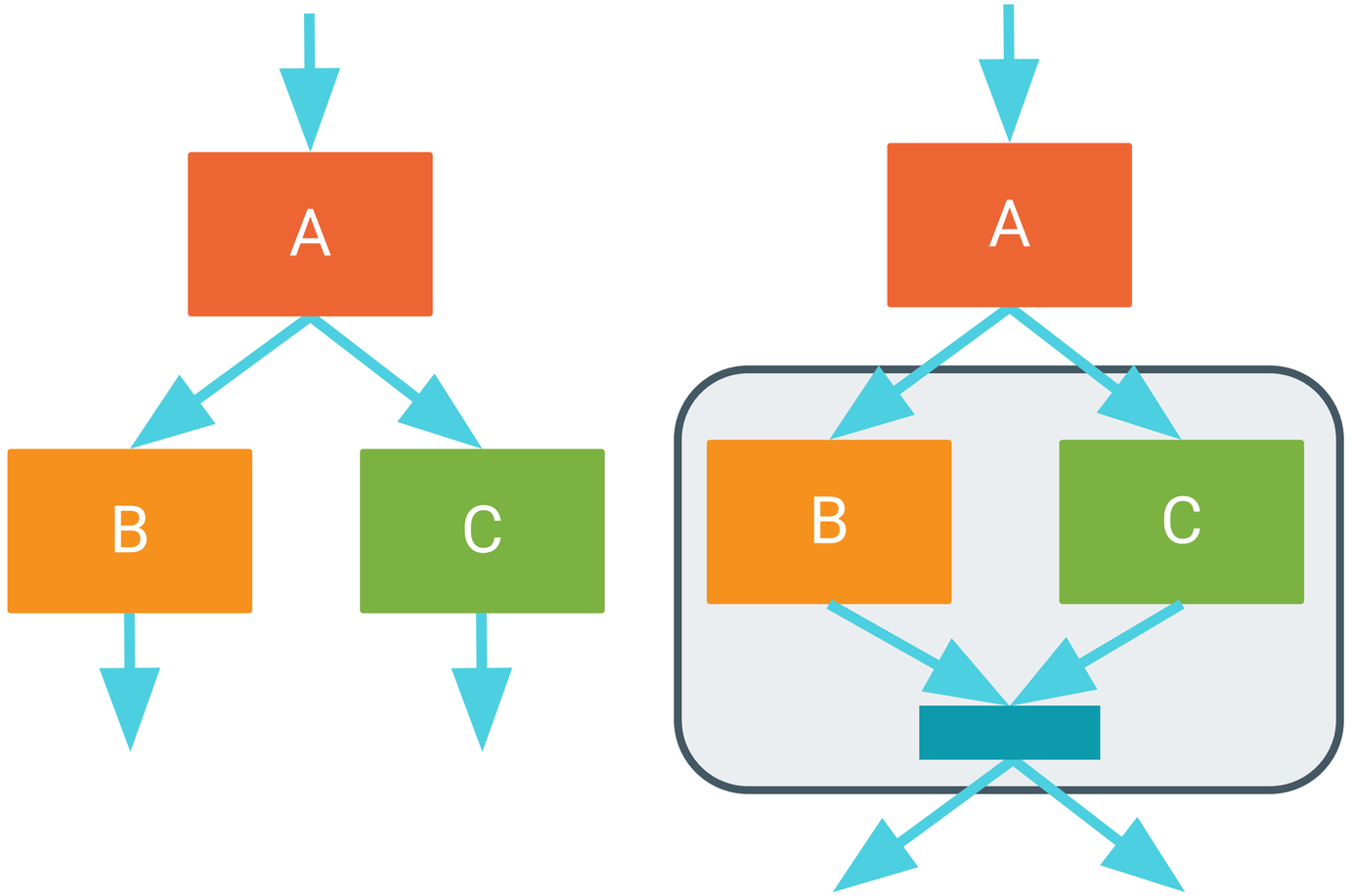
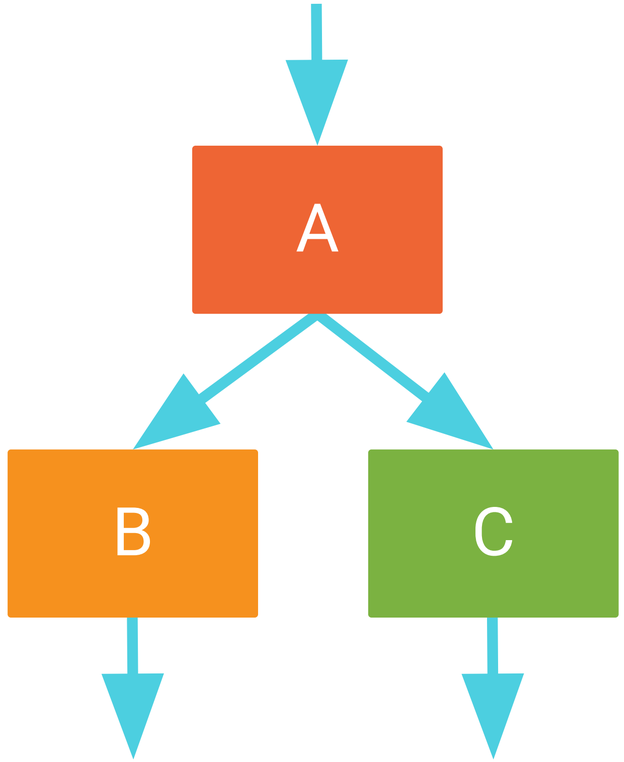
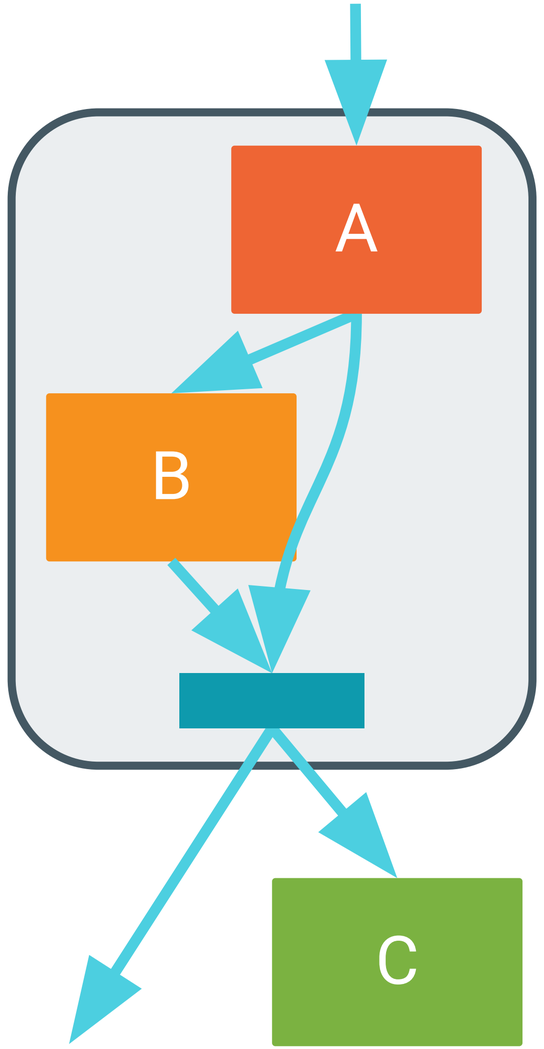


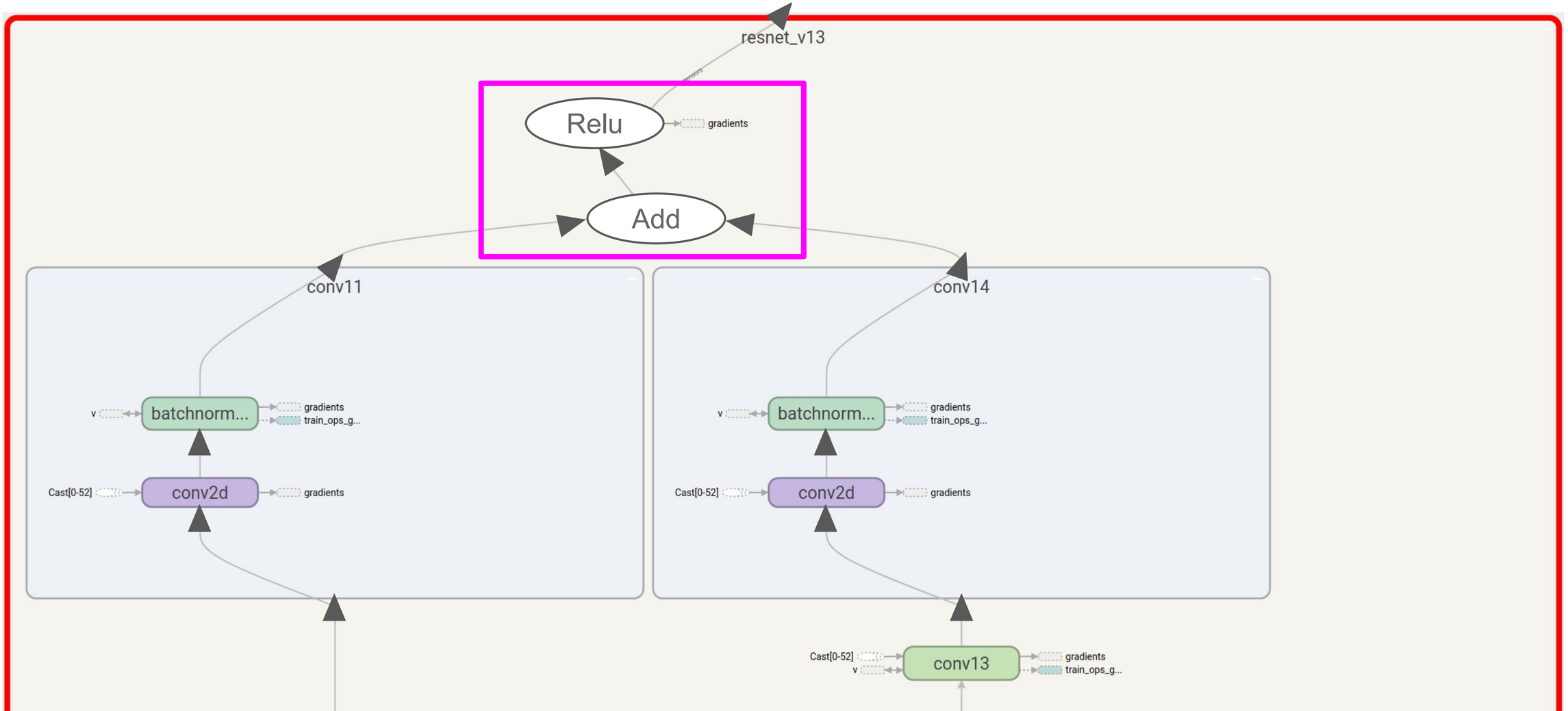
HLO Fusion

1) Fusion (with duplication)
2) Sibling fusion
3) Fusion with multiple outputs

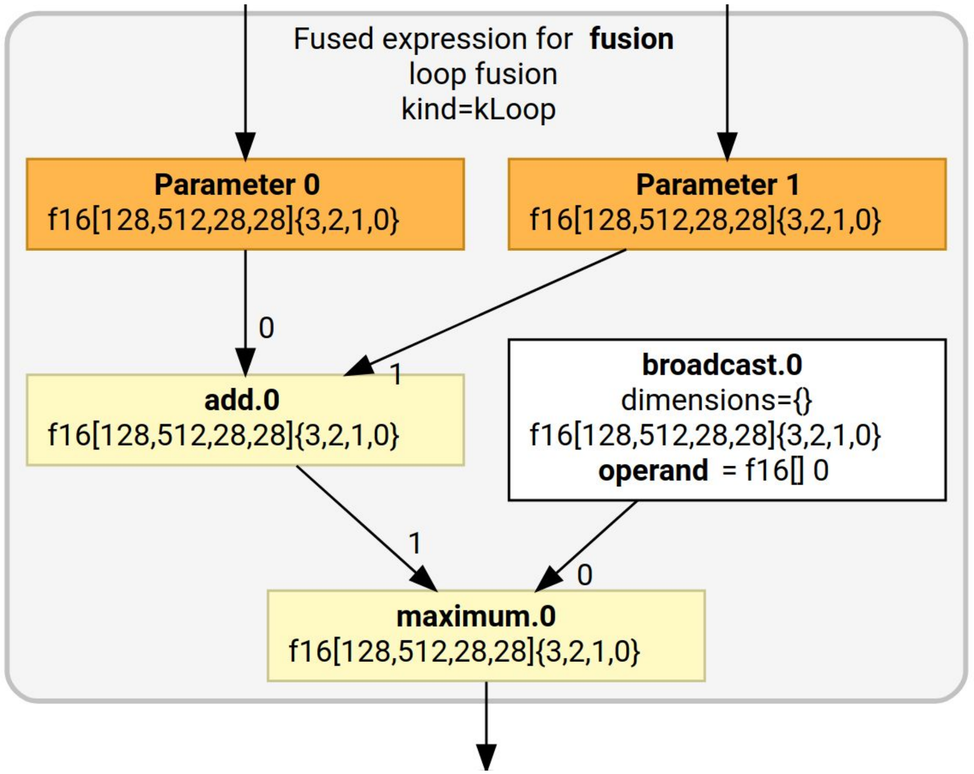




Example: ResNet block



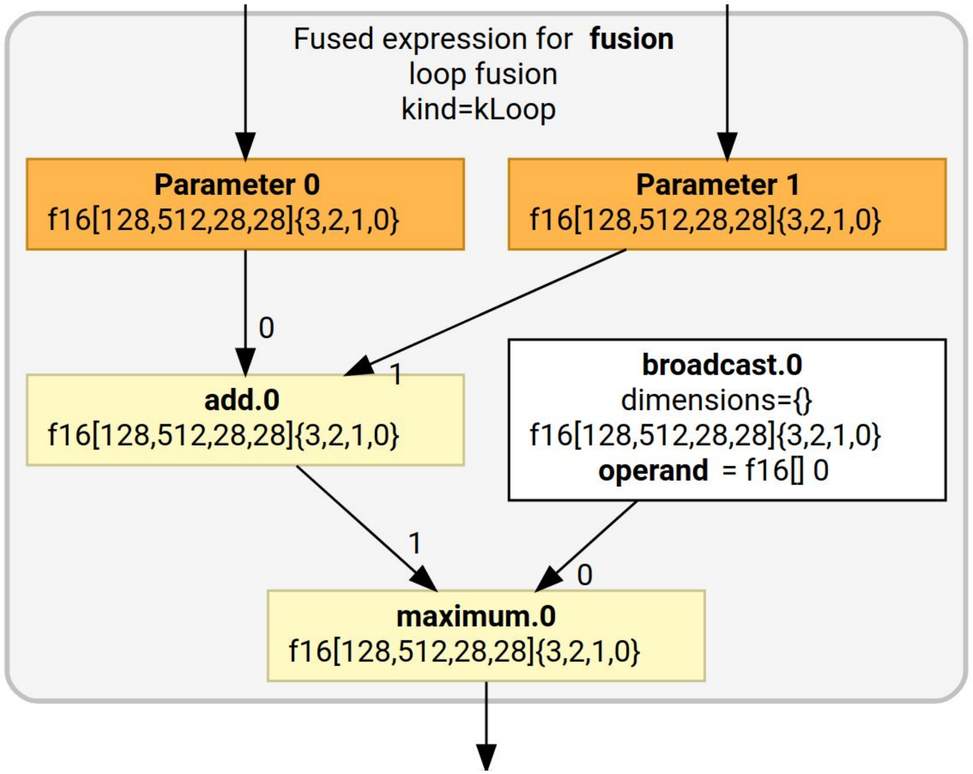
Fused Add + ReLu



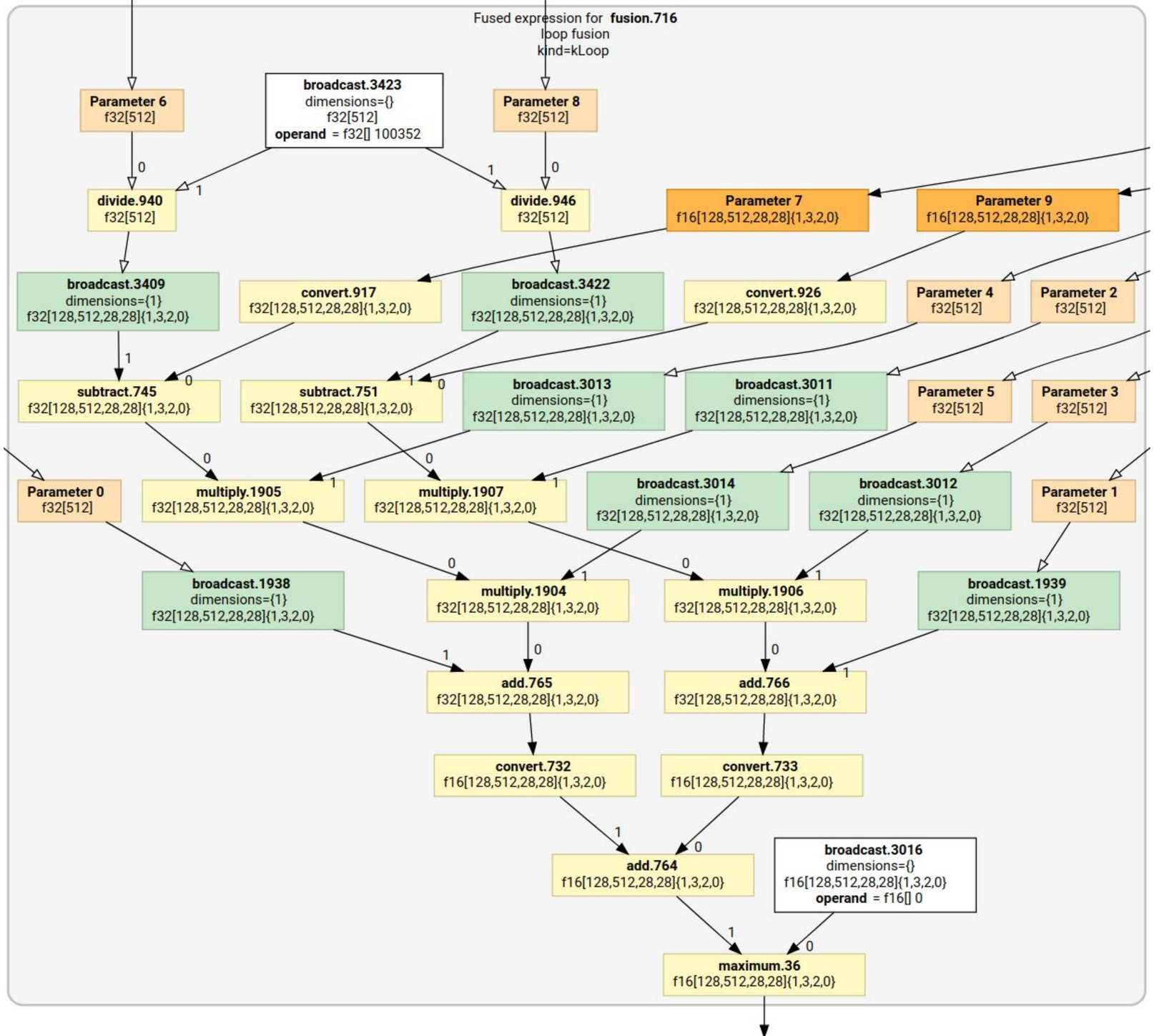

```
__global__ void fusion(float *lhs,
    float *rhs, float* output) {

  int i = blockIdx.x * blockDim.x +
          threadIdx.x;

  if (i < 128*512*28*28) {
    output[i] =
  }

}
```

```
std::function<llvm::Value*>(const IrArray::Index& index)
    MakeElementGenerator(const HloInstruction* hlo,
                         HloToElementGeneratorMap& operand_to_generator) {
  switch (hlo->opcode()) {
    case HloOpcode::kMaximum:
      return [...](const IrArray::Index& index) {
        llvm::Value* lhs =
            operand_to_generator.at(hlo->operand(0))(index);
        llvm::Value* rhs =
            operand_to_generator.at(hlo->operand(1))(index);
        auto cmp = b->CreateFCmpUGE(lhs, rhs);
        return ir_builder_->CreateSelect(cmp, lhs, rhs);
      };
    ...
  }
```

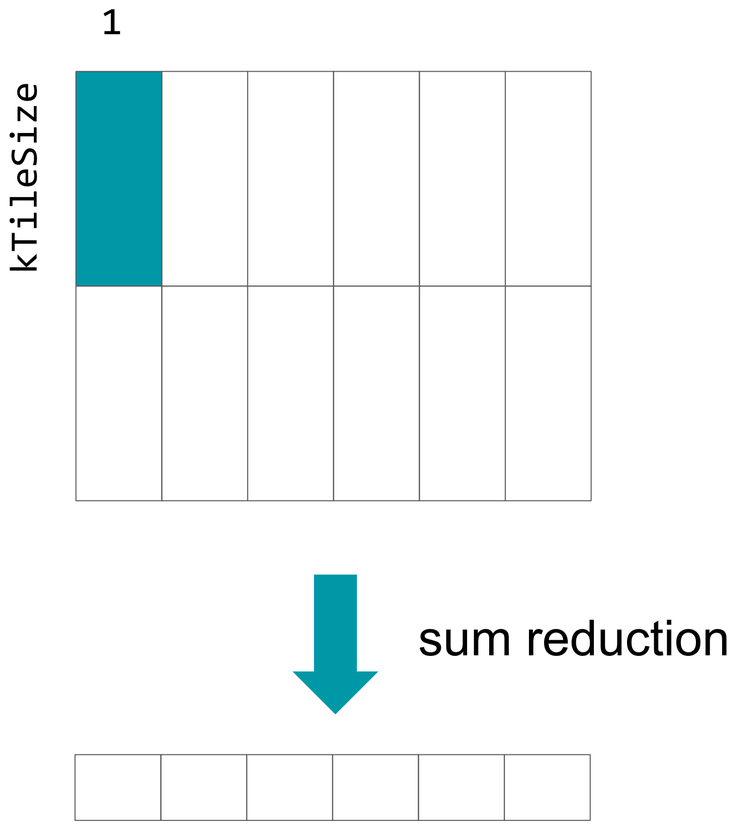
Fused Add + ReLu




```
__global__ void fusion(float *lhs,
    float *rhs, float* output) {

  int i = blockIdx.x * blockDim.x +
          threadIdx.x;

  if (i < 128*512*28*28) {
    output[i] =  max(0.0, lhs[i] + rhs[i]);
  }

}
```

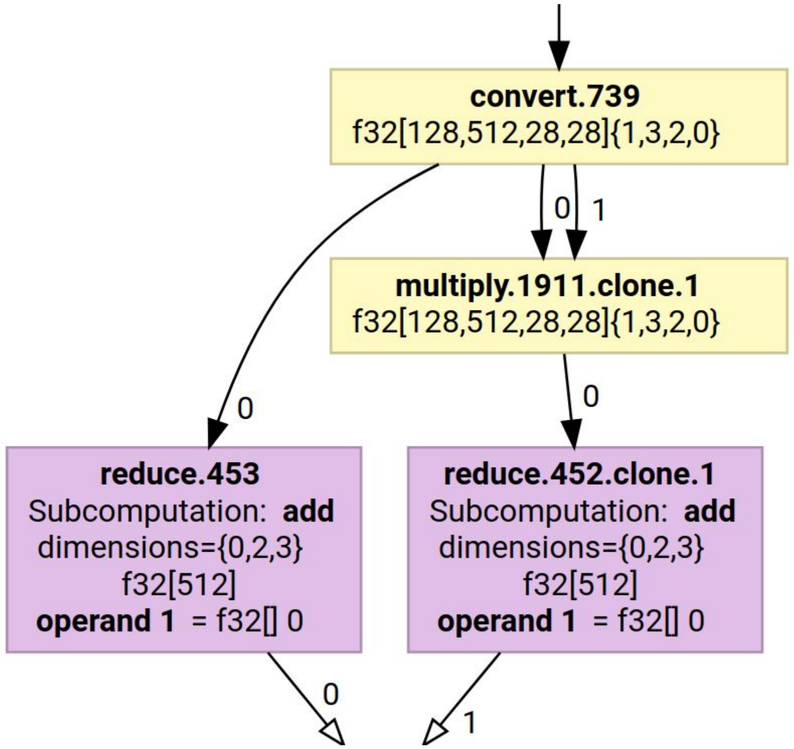

Fused expression for fusion.716
loop fusion
kind=kLoop
Parameter 6
f32[512]
broadcast.3423
dimensions={}
f32[512]
operand = f32[] 100352
Parameter 8
f32[512]
divide.940
f32[512]
divide.946
f32[512]
Parameter 7
f16[128,512,28,28]{1,3,2,0}
Parameter 9
f16[128,512,28,28]{1,3,2,0}
broadcast.3409
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
convert.917
f32[128,512,28,28]{1,3,2,0}
broadcast.3422
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
convert.926
f32[128,512,28,28]{1,3,2,0}
Parameter 4
f32[512]
Parameter 2
f32[512]
subtract.745
f32[128,512,28,28]{1,3,2,0}
subtract.751
f32[128,512,28,28]{1,3,2,0}
broadcast.3013
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
broadcast.3011
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
Parameter 5
f32[512]
Parameter 3
f32[512]
Parameter 0
f32[512]
multiply.1905
f32[128,512,28,28]{1,3,2,0}
multiply.1907
f32[128,512,28,28]{1,3,2,0}
broadcast.3014
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
broadcast.3012
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
Parameter 1
f32[512]
broadcast.1938
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
multiply.1904
f32[128,512,28,28]{1,3,2,0}
multiply.1906
f32[128,512,28,28]{1,3,2,0}
broadcast.1939
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
add.765
f32[128,512,28,28]{1,3,2,0}
add.766
f32[128,512,28,28]{1,3,2,0}
convert.732
f16[128,512,28,28]{1,3,2,0}
convert.733
f16[128,512,28,28]{1,3,2,0}
add.764
f16[128,512,28,28]{1,3,2,0}
broadcast.3016
dimensions={}
f16[128,512,28,28]{1,3,2,0}
operand = f16[] 0
maximum.36
f16[128,512,28,28]{1,3,2,0}

Reduction

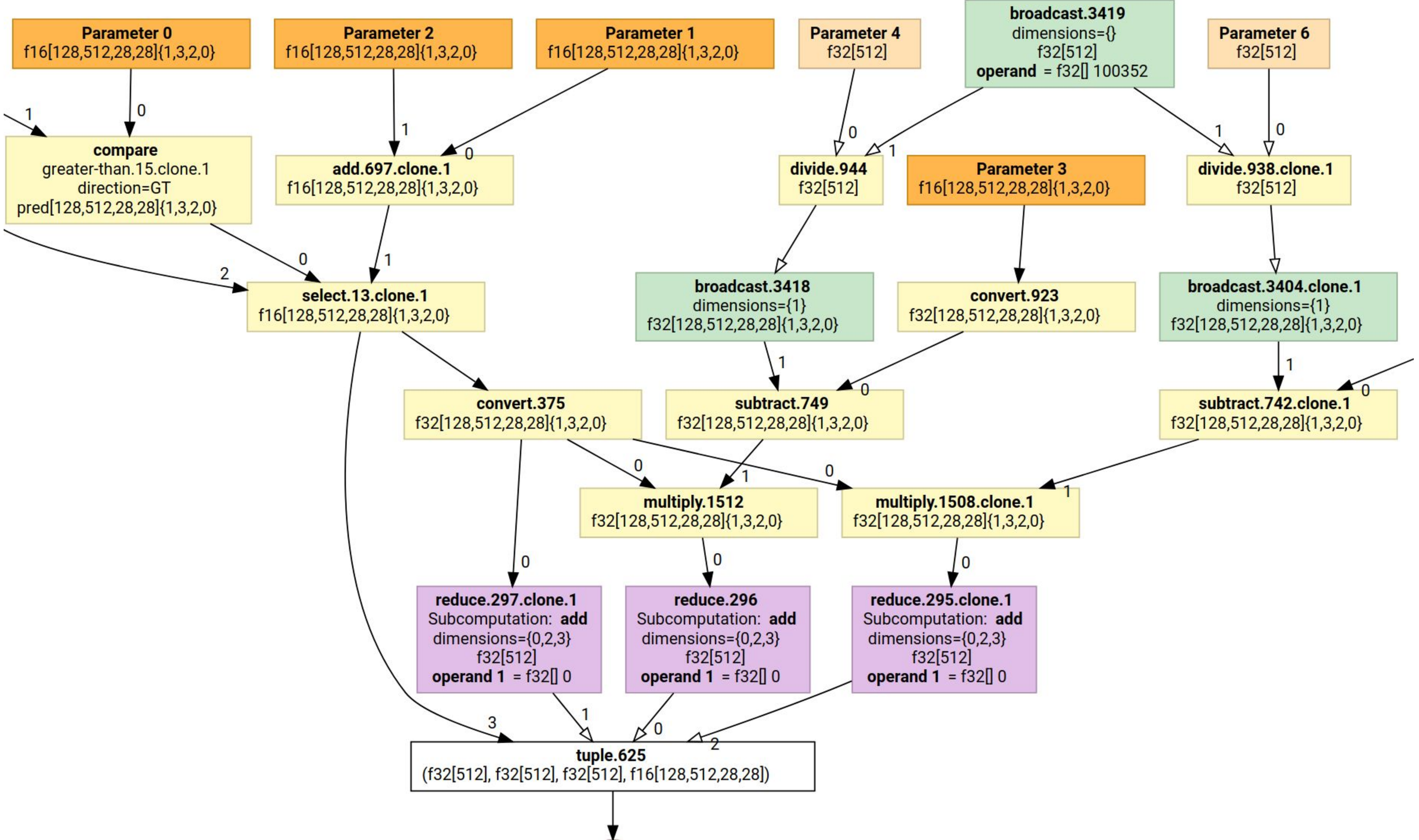



```
i = blockIdx.x * blockDim.x + threadIdx.x;
y_in_tiles = i / width;
x = i % width;

for (int j = 0; j < kTileSize: ++j) {
  y = y_in_tiles * kTileSize + j;
  if (y < height) {
    partial_sum += generator(y, x);
  }
}
atomicAdd(&output[x], partial_sum);
```

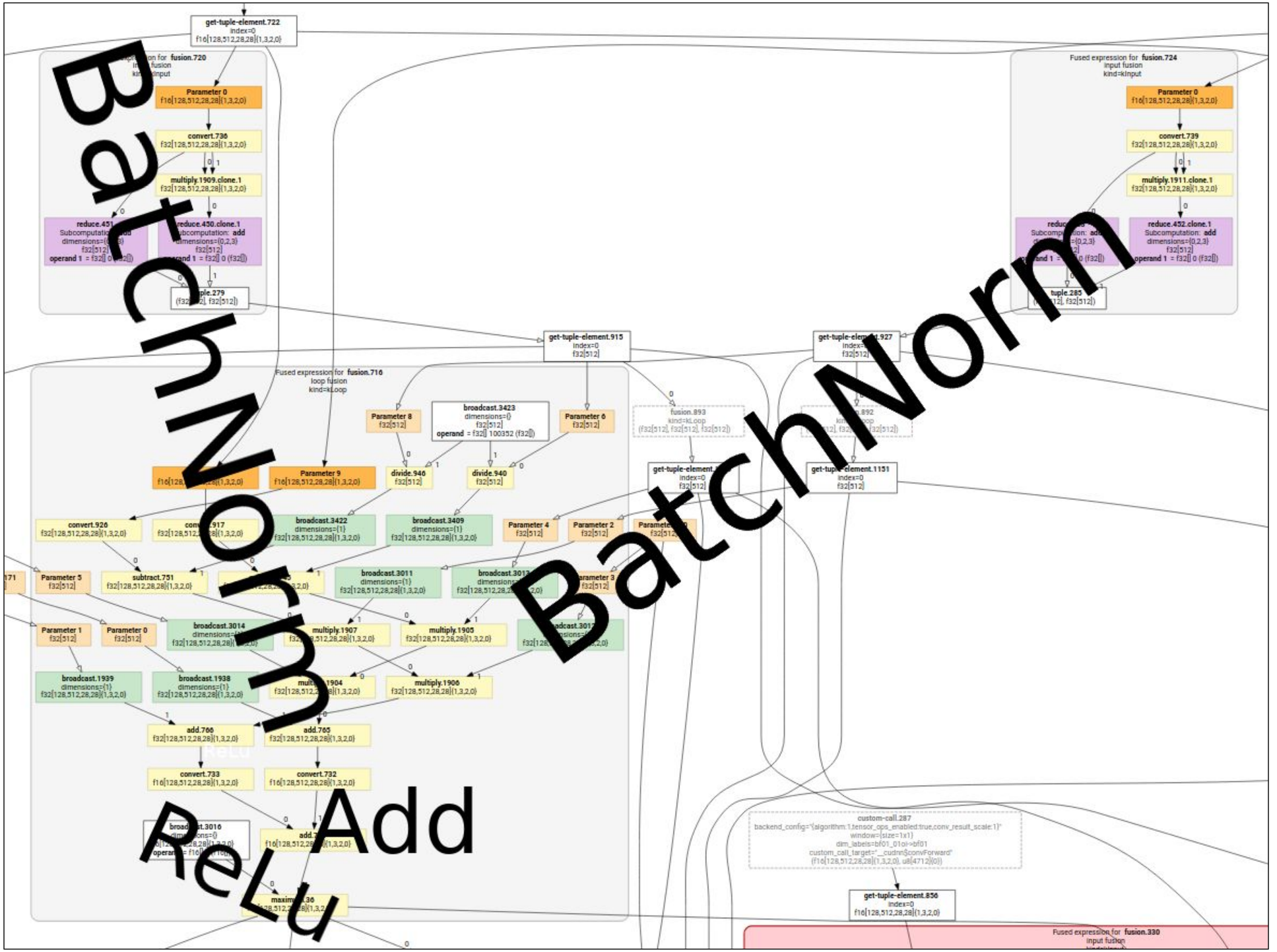
Multi-output fusion




```
i = blockIdx.x * blockDim.x + threadIdx.x;
y_in_tiles = i / width;
x = i % width;

for (int j = 0; j < kTileSize: ++j) {
  y = y_in_tiles * kTileSize + j;
  if (y < height) {
    partial_sum[0] += generator[0](y, x);
    partial_sum[1] += generator[1](y, x);
  }
}
atomicAdd(&output[0][x], partial_sum[0]);
atomicAdd(&output[1][x], partial_sum[1]);
```


Parameter 0
f16[128,512,28,28]{1,3,2,0}
Parameter 2
f16[128,512,28,28]{1,3,2,0}
Parameter 1
f16[128,512,28,28]{1,3,2,0}
Parameter 4
f32[512]
broadcast.3419
dimensions={}
f32[512]
operand = f32[] 100352
Parameter 6
f32[512]
compare
greater-than.15.clone.1
direction=GT
pred[128,512,28,28]{1,3,2,0}
add.697.clone.1
f16[128,512,28,28]{1,3,2,0}
divide.944
f32[512]
Parameter 3
f16[128,512,28,28]{1,3,2,0}
divide.938.clone.1
f32[512]
select.13.clone.1
f16[128,512,28,28]{1,3,2,0}
broadcast.3418
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
convert.923
f32[128,512,28,28]{1,3,2,0}
broadcast.3404.clone.1
dimensions={1}
f32[128,512,28,28]{1,3,2,0}
convert.375
f32[128,512,28,28]{1,3,2,0}
subtract.749
f32[128,512,28,28]{1,3,2,0}
subtract.742.clone.1
f32[128,512,28,28]{1,3,2,0}
multiply.1512
f32[128,512,28,28]{1,3,2,0}
multiply.1508.clone.1
f32[128,512,28,28]{1,3,2,0}
reduce.297.clone.1
Subcomputation: add
dimensions={0,2,3}
f32[512]
operand 1 = f32[] 0
reduce.296
Subcomputation: add
dimensions={0,2,3}
f32[512]
operand 1 = f32[] 0
reduce.295.clone.1
Subcomputation: add
dimensions={0,2,3}
f32[512]
operand 1 = f32[] 0
tuple.625
(f32[512], f32[512], f32[512], f16[128,512,28,28])

```
i = blockIdx.x * blockDim.x + threadIdx.x;
y_in_tiles = i / width;
x = i % width;

for (int j = 0; j < kTileSize: ++j) {
  y = y_in_tiles * kTileSize + j;
  if (y < height) {
    partial_sum[0] += generator[0](y, x);
    partial_sum[1] += generator[1](y, x);
    partial_sum[2] += generator[2](y, x);
    output[3][y, x] = generator[3](y, x);
  }
}
atomicAdd(&output[0][x], partial_sum[0]);
atomicAdd(&output[1][x], partial_sum[1]);
atomicAdd(&output[2][x], partial_sum[2]);
```


BatchNorm
BatchNorm
BatchNorm
Add
ReLu

Thank you! Questions?

XLA documentation
https://www.tensorflow.org/xla/overview

Public XLA mailing list
xla-dev@googlegroups.com

XLA on Github
https://github.com/tensorflow/tensorflow/tree/master/tensorflow/compiler