DLVM

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Deep Learning Compiler Technologies

XLA

PyTorch JIT

Latte.jl

NNVM / TVM

DLVM

ONNX

Typing

Compute

Optimizations

Static Analysis

Intermediate Representation

Neural networks are programs

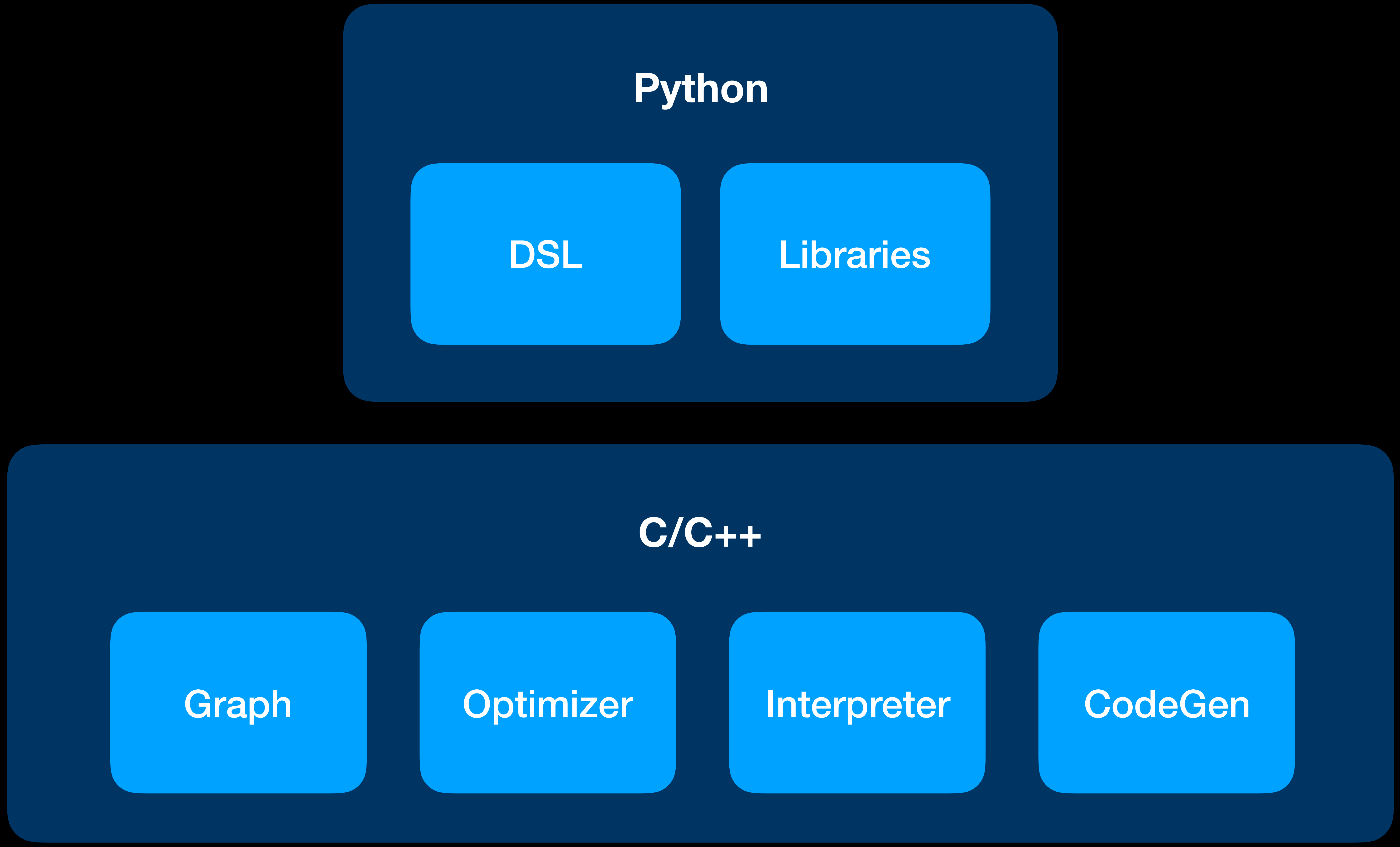
Control Flow

Automatic Differentiation

Auto Vectorization

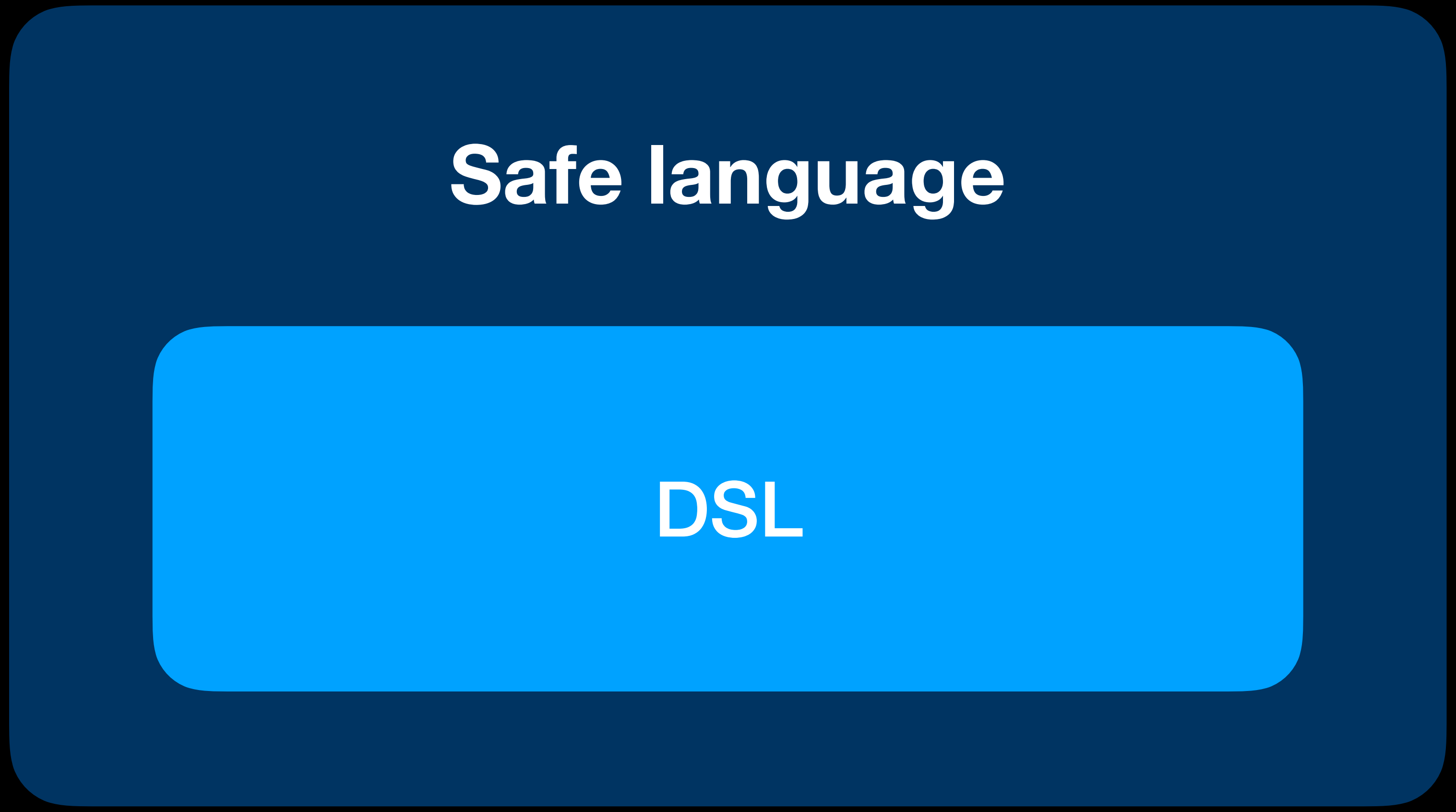
A New Compiler Problem

- Programs, not just a data flow graph
- Type safety
- Ahead-of-time AD
- Code generation
- Lightweight installation


Python
DSL
Libraries
C/C++
Graph
Optimizer
Interpreter
CodeGen

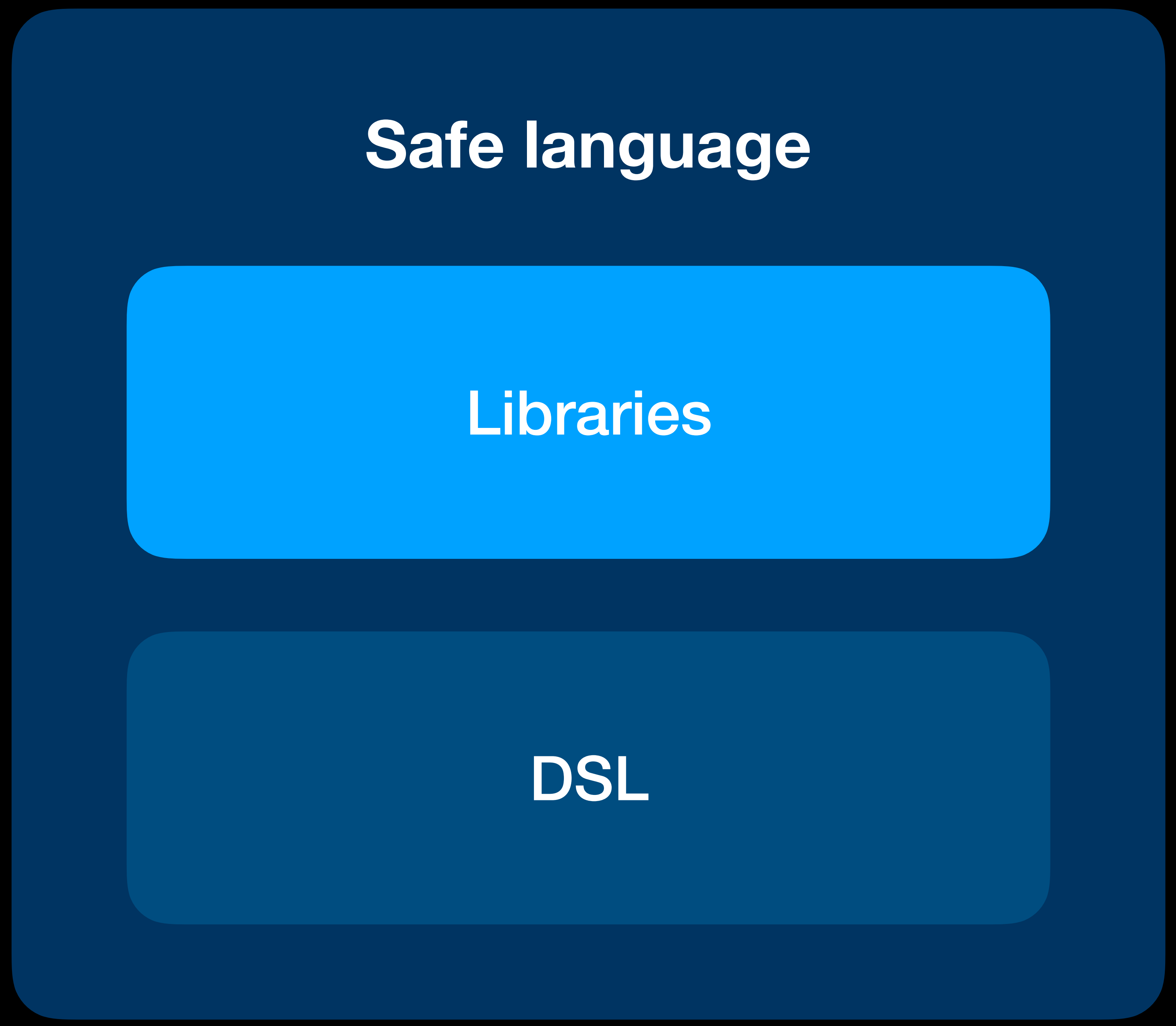
Python

Safe language



- NN as a host language function
- Type safety
- Naturalness
  - Lightweight modular staging*
  - Compiler magic

* Rompf, Tiark, and Martin Odersky. Lightweight Modular Staging: A Pragmatic Approach to Runtime Code Generation and Compiled DSLs, 2010



- Trainer
- Layers
- Application API

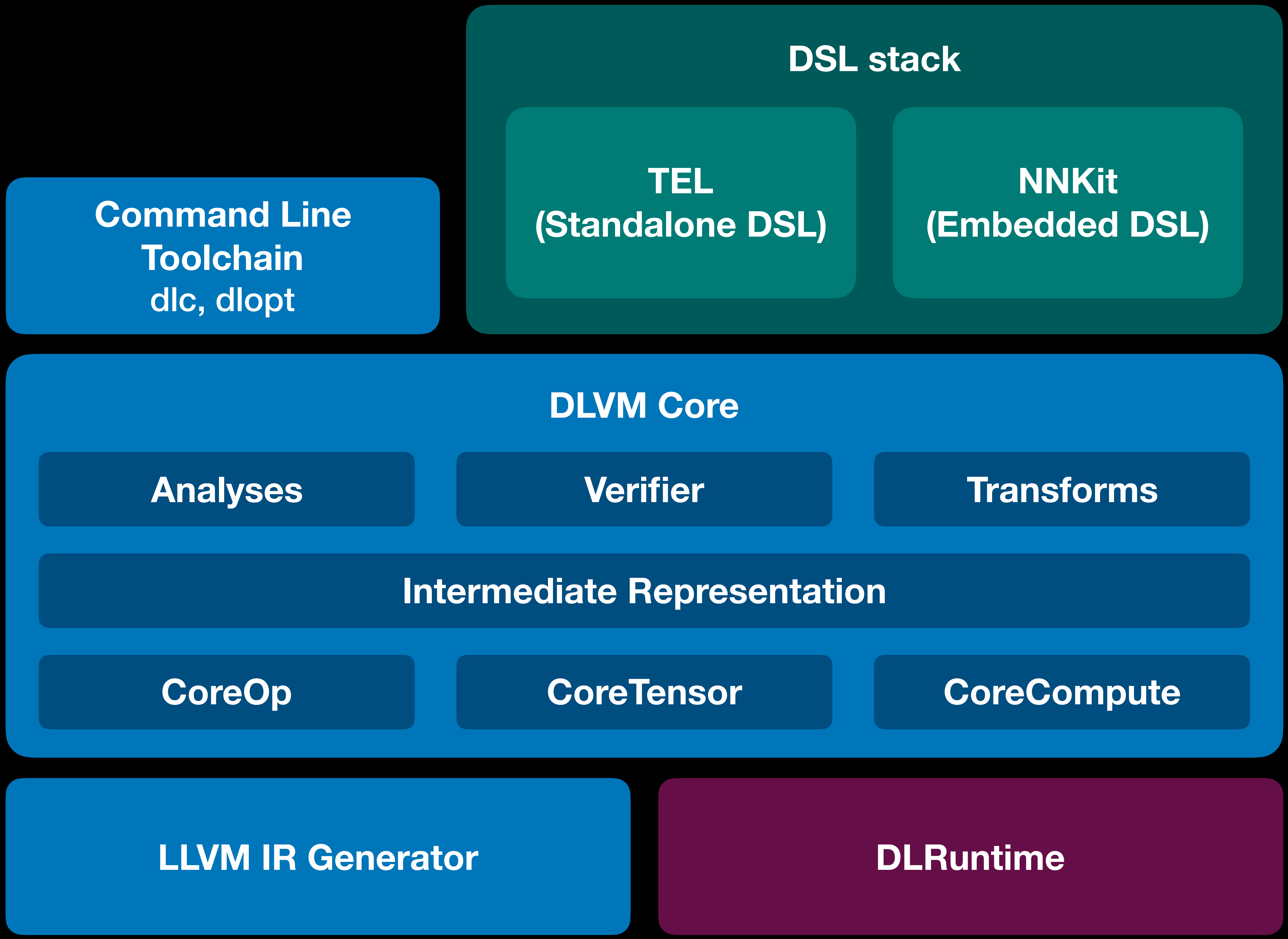
- Generic linear algebra IR
- Automatic differentiation
- Optimizations
- Code generation
- Runtime

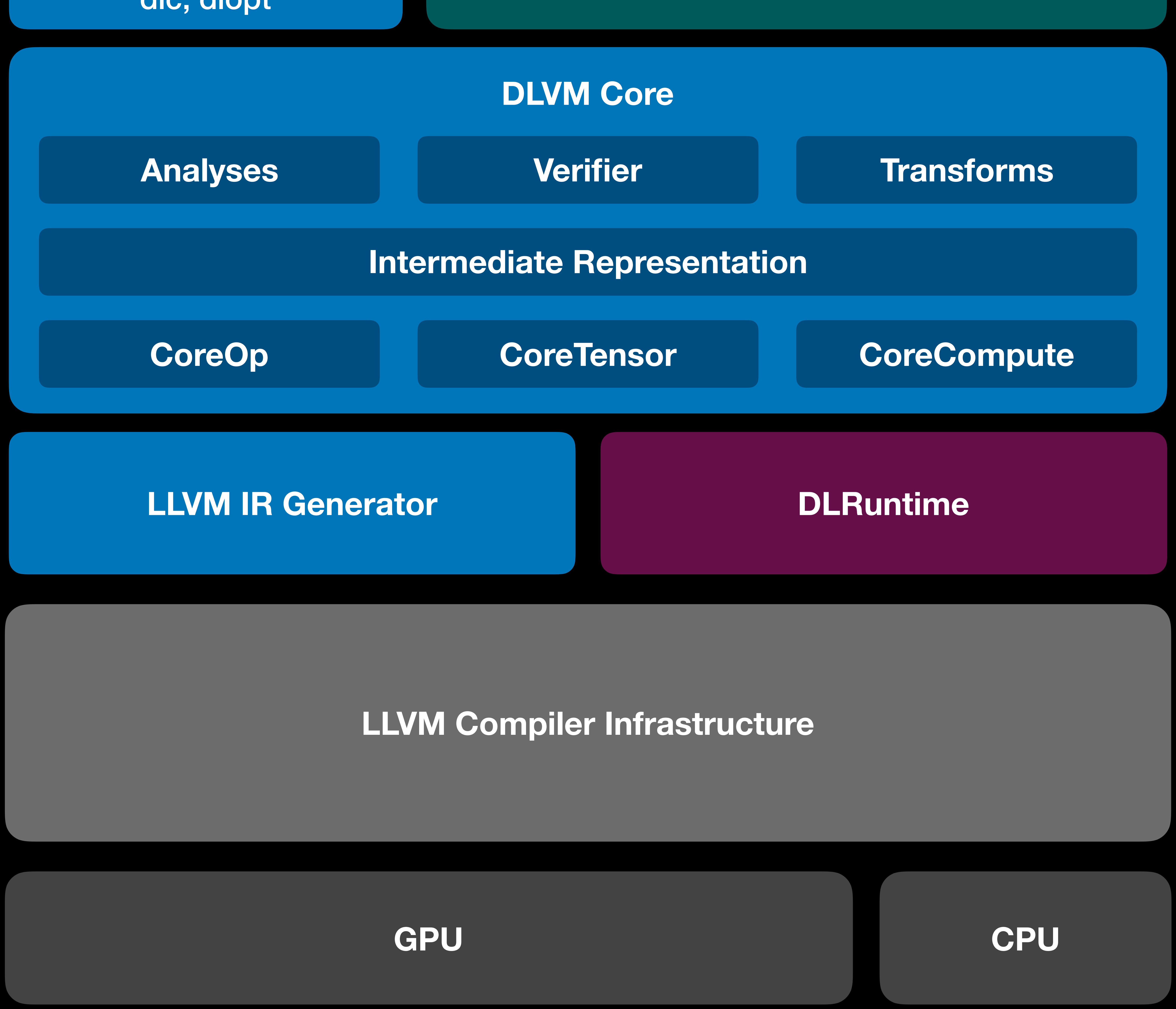
DSL

Compiler Infrastructure

DLVM

- Linear algebra IR
- Framework for building DSLs
- Automatic backpropagator
- Multi-stage optimizer
- Static code generator based on LLVM


DSL stack
TEL
(Standalone DSL)
NNKit
(Embedded DSL)
Command Line
Toolchain
dlc, dlopt
DLVM Core
Analyses
Verifier
Transforms
Intermediate Representation
CoreOp
CoreTensor
CoreCompute
LLVM IR Generator
DLRuntime


DLVM Core
Analyses
Verifier
Transforms
Intermediate Representation
CoreOp
CoreTensor
CoreCompute
LLVM IR Generator
DLRuntime
LLVM Compiler Infrastructure
GPU
CPU

Core Language:
DLVM IR

Tensor Type

Rank	Notation	Descripton
0	`i64`	64-bit integer
1	`<100 x f32>`	float vector of size 100
2	`<100 x 300 x f64>`	double matrix of size 100x300
n	`<100 x 300 x ... x bool>`	rank-n tensor

First-class tensors

Domain-Specific Instructions

Kind	Example
Element-wise unary	`tanh %a: <10 x f32>`
Element-wise binary	`power %a: <10 x f32>, %b: 2: f32`
Dot	`dot %a: <10 x 20 x f32>, %b: <20 x 2 x f32>`
Concatenate	`concatenate %a: <10 x f32>, %b: <20 x f32> along 0`
Reduce	`reduce %a: <10 x 30 x f32> by add along 1`
Transpose	`transpose %m: <2 x 3 x 4 x 5 x i32>`
Convolution	`convolve … kernel … strides … padding … dilation … groups …`
Slice	`slice %a: <10 x 20 x i32> from 1 upto 5`
Random	`random 768 x 10 from 0.0: f32 upto 1.0: f32`
Select	`select %x: <10 x f64>, %y: <10 x f64> by %flags: <10 x bool>`
Compare	`greaterThan %a: <10 x 20 x bool>, %b: <1 x 20 x bool>`
Data type cast	`dataTypeCast %x: <10 x i32> to f64`

General-Purpose Instructions

Kind	Example
Function application	`apply %foo(%x: f32, %y: f32): (f32, f32) -> <10 x 10 x f32>`
Branch	`branch 'block_name(%a: i32, %b: i32)`
Conditional (if-then-else)	`conditional %cond: bool then 'then_block() else 'else_block()`
Shape cast	`shapeCast %a: <1 x 40 x f32> to 2 x 20`
Extract	`extract #x from %pt: $Point`
Insert	`insert 10: f32 to %pt: $Point at #x`
Allocate stack	`allocateStack $Point count 1`
Allocate heap	`allocateHeap $MNIST count 1`
Deallocate	`deallocate %x: *<10 x f32>`
Load	`load %ptr: *<10 x i32>`
Store	`store %x: <10 x i32> to %ptr: *<10 x i32>`
Copy	`copy from %src: *<10 x f16> to %dst: *<10 x f16> count 1: i64`

Instruction Set

- Primitive math operators & general purpose operators
- No **softmax, sigmoid**
  - Composed by primitive math ops
- No **min, max, relu**
  - Composed by **compare** & **select**

DLVM IR

- Full static single assignment (SSA) form
  - Control flow graph (CFG) and basic blocks with arguments
- Custom type definitions
- Modular architecture (module - function - basic block - instruction)
- Textual format & in-memory format
  - Built-in parser and verifier
  - Robust unit testing via LLVM Integrated Tester (lit) and FileCheck

DLVM IR


Module
Function
Basic Block
Basic Block
Basic Block
Function
Basic Block
Basic Block
Basic Block
Type Definition

```
module "my_module" // Module declaration
stage raw          // Raw stage IR in the compilation phase

struct $Classifier {
    #w: <784 x 10 x f32>,
    #b: <1 x 10 x f32>,
}

type $MyClassifier = $Classifier
```

```
module "my_module" // Module declaration
stage raw          // Raw stage IR in the compilation phase

struct $Classifier {
    #w: <784 x 10 x f32>,
    #b: <1 x 10 x f32>,
}

type $MyClassifier = $Classifier

func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}
```

```
module "my_module" // Module declaration
stage raw          // Raw stage IR in the compilation phase

struct $Classifier {
    #w: <784 x 10 x f32>,
    #b: <1 x 10 x f32>,
}

type $MyClassifier = $Classifier

func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    conditional true: bool then ‘b0() else 'b1()
'b0():
    return %0.1: <1 x 10 x f32>
‘b1():
    return 0: <1 x 10 x f32>
}
```

Transformations:
Differentiation & Optimizations

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @inference wrt 1, 2]
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>)
```

Differentiation Pass

Canonicalizes every gradient function declaration in an IR module

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}


func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>) {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):

        Copy instructions from original function



}
```

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}


func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>) {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>

       Generate adjoint code


}
```

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}
```

```
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>) {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    %0.2 = transpose %x: <1 x 784 x f32>
    %0.3 = dot %0.2: <784 x 1 x f32>, 1: <1 x 10 x f32>
    %0.4 = literal (%0.3: <784 x 10 x f32>, 1: <1 x 10 x f32>): (<784 x 10 x f32>, <1 x 10 x f32>)
    return %0.4: (<784 x 10 x f32>, <1 x 10 x f32>)
}
```

Dead Code Elimination Pass

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}


func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>) {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = transpose %x: <1 x 784 x f32>
    %0.1 = dot %0.0: <784 x 1 x f32>, 1: <1 x 10 x f32>
    %0.2 = literal (%0.1: <784 x 10 x f32>, 1: <1 x 10 x f32>): (<784 x 10 x f32>, <1 x 10 x f32>)
    return %0.2: (<784 x 10 x f32>, <1 x 10 x f32>)
}
```

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @inference from 0]
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
```

Configurable gradient declaration

`from`: selecting which output to differentiate in tuple return

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @inference from 0 wrt 1, 2]
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>)
```

Configurable gradient declaration

`from`: selecting which output to differentiate in tuple return

`wrt`: with respect to arguments 1 & 2

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @inference from 0 wrt 1, 2 keeping 0]
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>, <1 x 10 x f32>)
```

Configurable gradient declaration

`from`: selecting which output to differentiate in tuple return

`wrt`: with respect to arguments 1 & 2

`keeping`: keeping original output

```
func @inference: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @inference from 0 wrt 1, 2 keeping 0 seedable]
func @inference_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>, <1 x 10 x f32>)
                    -> (<784 x 10 x f32>, <1 x 10 x f32>, <1 x 10 x f32>)
```

Configurable gradient declaration

`from`: selecting which output to differentiate in tuple return

`wrt`: with respect to arguments 1 & 2

`keeping`: keeping original output

`seedable`: allow passing in back-propagated gradients as seed

```
func @f: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

func @g: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = apply @f(%x, %w, %b): (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32>
    %0.1 = tanh %0.0: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}
```

```
func @f: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

func @g: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = apply @f(%x, %w, %b): (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32>
    %0.1 = tanh %0.0: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @g wrt 1, 2]
func @g_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> (<784 x 10 x f32>, <1 x 10 x f32>)
```

```
func @f: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

func @g: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = apply @f(%x, %w, %b): (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32>
    %0.1 = tanh %0.0: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}

[gradient @g wrt 1, 2]
func @g_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> (<784 x 10 x f32>, <1 x 10 x f32>)

[gradient @f wrt 1, 2 seedable]
func @f_grad: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>, <1 x 10 x f32>)
             -> (<784 x 10 x f32>, <1 x 10 x f32>)
```

Seed

Compilation Phases

`stage raw` `stage optimizable` `stage compute` `stage schedule`

DLVM → Analyses & Verification → Differentiation → Optimizations → Compute Generation → Compute Scheduling → LLGen → LLVM

Analyses & Verification
- Dominance
- Side Effects
- Type Checking
- Differentiability

Optimizations
- Algebra Simp
- AD Checkpointing
- Linear Alg Fusion
- Matrix Chaining
- Constant Prop
- Dead Code Elim
- Com Subexpr Elim

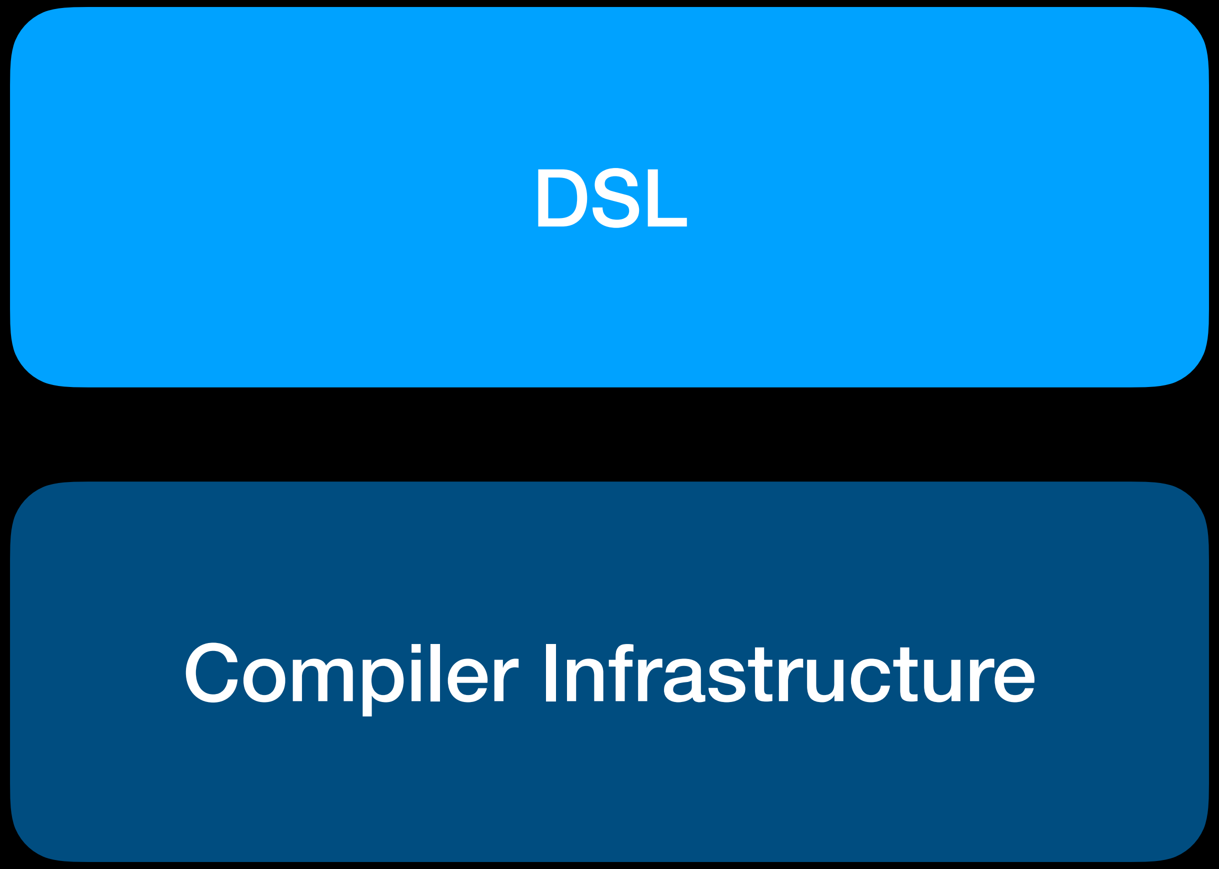
DLVM

DSL

Compiler Infrastructure

DSL

Compiler Infrastructure



- NN as program, not a graph
- Static analysis
- Type safety
- Naturalness
  - Lightweight modular staging
  - Compiler magic

NNKit: Staged DSL in Swift

NNKit

- It’s a prototype!
- Tensor computation embedded in host language
- Type safety
- Generates DLVM IR on the fly

Language

- Statically ranked tensors
  - `T, Tensor1D<T>, Tensor2D<T>, Tensor3D<T>, Tensor4D<T>`
- Type wrapper for staging – `Rep<Wrapped>`
  - `Rep<Float>, Rep<Tensor1D<Float>>, Rep<Tensor2D<T>>`
- Operator overloading
  - `func + <T: Numeric>(_: Rep<T>, _: Rep<T>) -> Rep<T>`
  - `func • (_: Rep<Tensor2D<T>>, _: Rep<Tensor2D<T>>) -> Rep<Tensor2D<T>>`

Language

- Lambda abstraction
  - `func lambda<T, U>(_ f: (Rep<T>) -> Rep<U>) -> Rep<(T) -> U>`
- Function application
  - `subscript<T, U>(arg: Rep<T>) -> Rep<U> where Wrapped == (T) -> U`
  - `subscript<T, U>(arg: T) -> U where Wrapped == (T) -> U`
    `// JIT DLVM IR`

Staged Evaluation

```
Rep<(Float2D) -> Float2D>
```

```
(Float2D) -> Float2D
```

Staged Evaluation

Expression Staging → Shape Specialization → DLVM IR Generation → → → Function Reification

```
Rep<(Float2D) -> Float2D>
```

```
(Float2D) -> Float2D
```

```
typealias Float2D = Tensor2D<Float>
```

```swift
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}
```

```swift
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}

let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
```

```
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}

let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }
```

```swift
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}

let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

let params: Parameters = …
```

```
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}

let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

let params: Parameters = …
let x: Float2D = [[0.0, 1.0]]
```

```
typealias Float2D = Tensor2D<Float>

struct Parameters {
    var w: Float2D
    var b: Float2D
}

let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

let params: Parameters = …
let x: Float2D = [[0.0, 1.0]]
f[x, params.w, params.b]  // ==> result
```

```
let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

f[x, w, b]
// x: 1x784, w: 784x10, b: 1x10


func @f: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>) -> <1 x 10 x f32> {
'entry(%x: <1 x 784 x f32>, %w: <784 x 10 x f32>, %b: <1 x 10 x f32>):
    %0.0 = dot %x: <1 x 784 x f32>, %w: <784 x 10 x f32>
    %0.1 = add %0.0: <1 x 10 x f32>, %b: <1 x 10 x f32>
    return %0.1: <1 x 10 x f32>
}
```

```
let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }
```

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// ∇g : Rep<(Float2D, Float2D, Float2D) -> (Float2D, Float2D)>

∇g[x, w, b] // ==> (∂g/∂w, ∂g/∂b )
[gradient @f wrt 1, 2]
func @g: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
         -> (<784 x 10 x f32>, <1 x 10 x f32>)
```

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[gradient @f wrt 1, 2]
func @g: (<1 x 784 x f32>, <784 x 10 x f32>, <1 x 10 x f32>)
         -> (<784 x 10 x f32>, <1 x 10 x f32>)
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let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

let g = lambda { x, w, b in
    let linear = f[x, w, b]
    return tanh(linear)
}

let ∇g = gradient(of: g, withRespectTo: (1, 2), seedable: true)
// ∇g : Rep<(Float2D, Float2D, Float2D, Float2D) -> (Float2D, Float2D)>
```

```
let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
        x • w + b
    }

let g = lambda { x, w, b in
    let linear = f[x, w, b]
    return tanh(linear)
}

let ∇g = gradient(of: g, withRespectTo: (1, 2), seedable: true, keeping: (0))
// ∇g : Rep<(Float2D, Float2D, Float2D, Float2D) -> (Float2D, Float2D, Float2D)>
```

```
let f: Rep<(Float2D, Float2D, Float2D) -> Float2D> =
    lambda { x, w, b in
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}

let ∇g = gradient(of: g, withRespectTo: (1, 2), seedable: true, keeping: (0))
// ∇g : Rep<(Float2D, Float2D, Float2D, Float2D) -> (Float2D, Float2D, Float2D)>

∇g[x, w, b, ∂h_∂g] // ==> ( ∂h/∂w, ∂h/∂b, g(x,w,b) )
```


Safe language
Libraries
DSL
Compiler Infrastructure

Swift

Libraries

NNKit

DLVM

DLVM is written in Swift!

PL & Compilers + ML

- Programs, not just a data flow graph
- Type safety
- Ahead-of-time AD
- Code generation

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