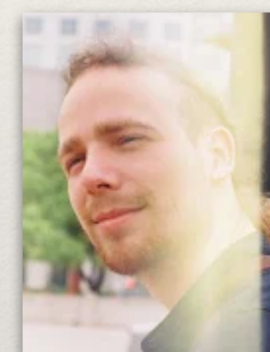
Making ML Fast for Arbitrary Code



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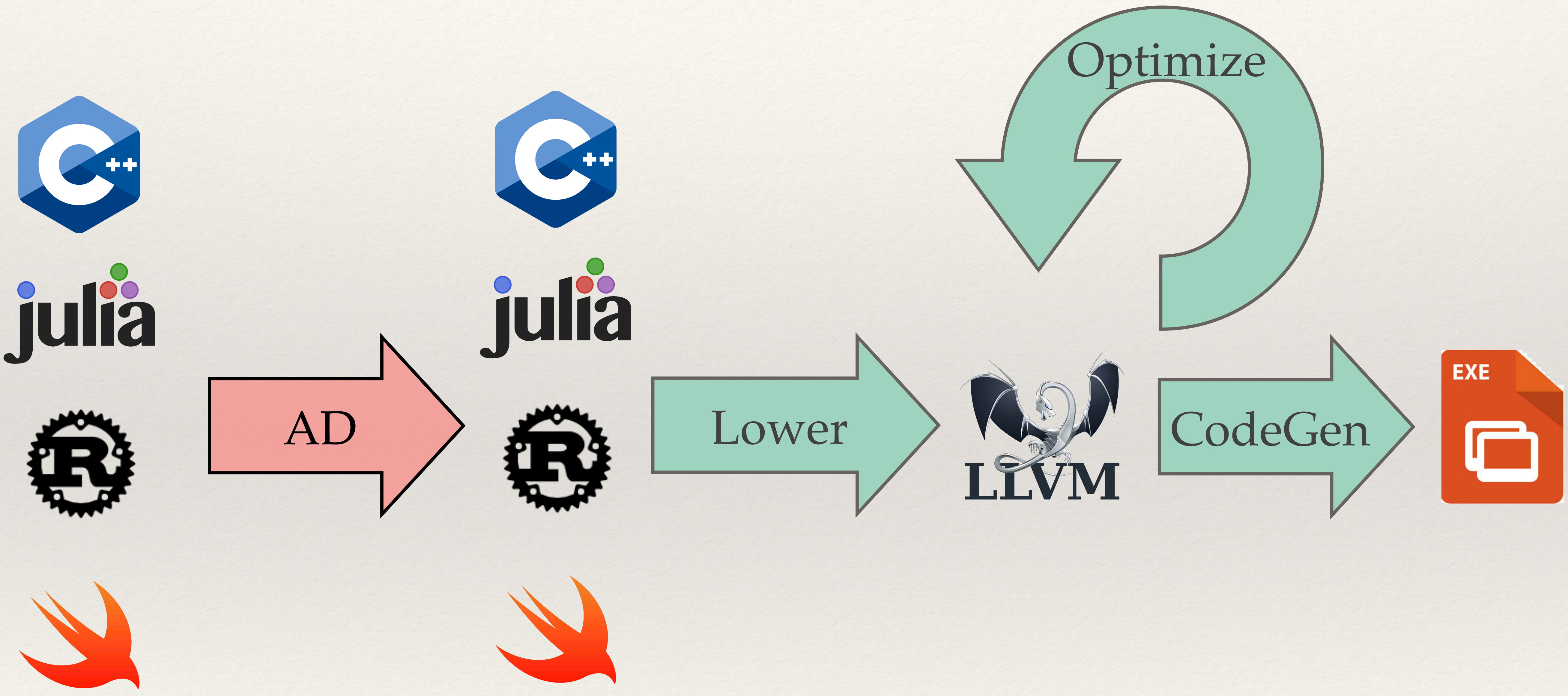
Automatic Differentiation

- Computing the derivatives of functions is necessary component in machine learning (back-propagation, Bayesian inference, uncertainty quantification), scientific computing (modeling, simulation), and other fields
- Writing derivatives of large codebases is intractable
- Existing solutions:
  - Differentiable DSL (TensorFlow, PyTorch, DiffTaichi)
  - Operator-overloading AD (Adept, ADOL-C, JAX)
  - Source-rewriting (Tapenade, ADIC, Zygote)

Operator Overloading vs Source Writing

- Operator overloading
  - Provide differentiable versions of existing language constructs
  - May require rewriting to use non-standard language utilities
  - Often dynamic: storing instructions & values of the forward pass in a tape that is later "interpreted" by the reverse pass
- Source rewriting
  - Statically analyze program to produce a new gradient function in the source language
  - Requires all differentiated code ahead of time; difficult to use with external libraries

Existing AD Pipelines



Case Study: Vector Normalization

```
//Compute magnitude in O(n)
double mag(double* x, size_t n);

//Compute norm in O(n^2)
void norm(double* out, double* in, size_t n) {
 for(int i=0; i<n; i++) {
    out[i] = in[i]/mag(in, n);
  }
}
```

$O(n^2)$

```
double mag(double* x, size_t n);

void norm(double* out, double* in, size_t n) {
 for(int i=0; i<n; i++) {
    out[i] = in[i]/mag(in, n);
  }
}
```

Loop Invariant Code Motion

$O(n)$

```
double mag(double* x, size_t n);

void norm(double* out, double* in, size_t n) {
  double res = mag(in, n);

  for(int i=0; i<n; i++) {
    out[i] = in[i]/res;
  }
}
```

LICM then AD

```
void dnorm(double* out, double* dout,
           double* in,  double* din, size_t n) {
  double res = mag(in, n);

  for(int i=0; i<n; i++) {
    out[i] = in[i]/res;
  }

  double d_res = 0;
  for(int i=0; i<n; i++) {
    dres += -in[i]*in[i]/res * dout[i];
    din[i] += dout[i]/res;
  }

  dmag(in, din, n, dres);
}
```

$O(n)$

$O(n)$

AD

```
void dnorm(double* out, double* dout,
           double* in,  double* din, size_t n) {

  for(int i=0; i<n; i++) {
    out[i] = in[i]/mag(in, n);
  }

  for(int i=0; i<n; i++) {
    double dres = -in[i]*in[i]/mag * dout[i];
    din[i] += dout[i]/mag;
    dmag(in, din, n, dres);
  }
}
```

$O\left(n^2\right)$

$O\left(n^2\right)$

AD then LICM

```
void dnorm(double* out, double* dout,
           double* in,  double* din, size_t n) {

  double res = mag(in, n);
  for(int i=0; i<n; i++) {
    out[i] = in[i]/res;
  }

  for(int i=0; i<n; i++) {
    double dres = -in[i]*in[i]/res * dout[i];
    din[i] += dout[i]/res;
    dmag(in, din, n, dres);
  }
}
```

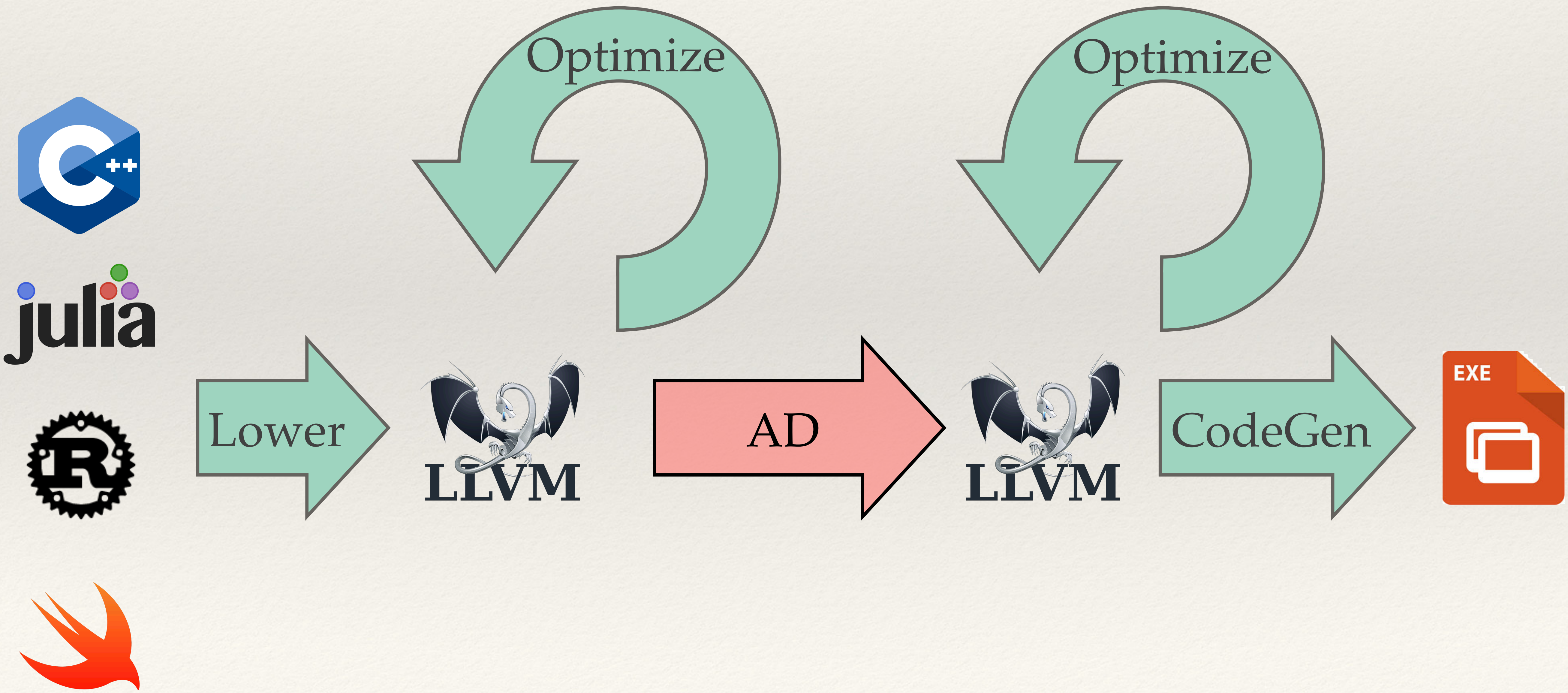
$O(n)$

$O(n^2)$

Can't LICM dmag as it uses loop-local dres

Enzyme Approach

Perform AD on *optimized* programs



Challenges of post-optimization AD

- Implement all optimizations in AD system
  - Embed a compiler into your AD
  - Rewrite all compiler analyzes and optimizations
- Perform AD on low-level post-optimization representation
  - Embed AD into your compiler
  - "AD is more effective in high-level compiled languages (e.g. Julia, Swift, Rust, Nim) than traditional ones such as C/C++, Fortran and LLVM IR […]" -Innes

Enzyme

- Reverse-mode source-rewriting AD plugin for statically analyzable LLVM IR
- 4.5x speedup over AD before optimization
- State-of-the art performance with existing tools
- Differentiates code in a variety of languages (C, C++, Fortran, Julia, Rust, Swift, etc)
- PyTorch-Enzyme/TensorFlow-Enzyme packages to let researchers use foreign code in their ML workflow
- Multisource AD & library support by leveraging LTO

ML Framework Integration

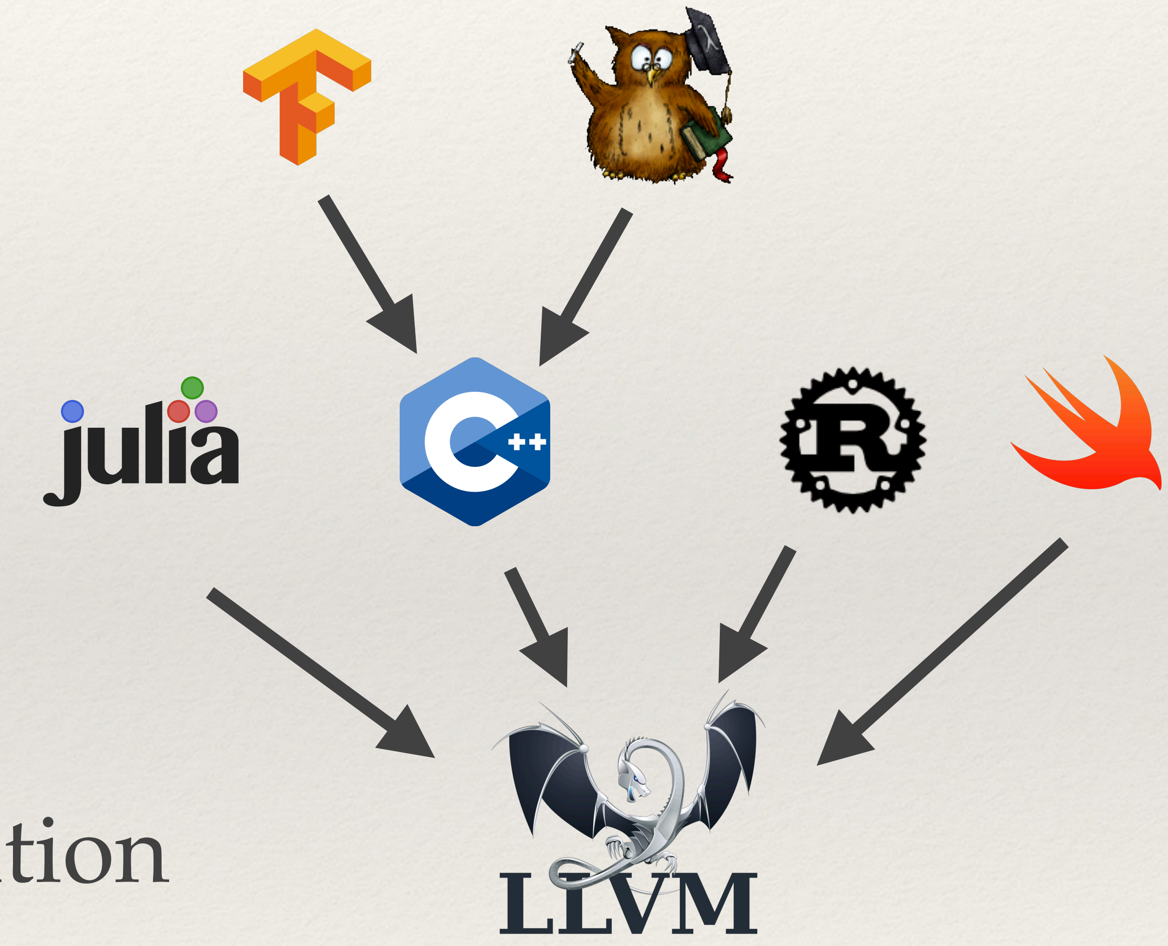
```python
import torch
from torch_enzyme import enzyme

# Create some initial tensor
inp = …

# Apply foreign function to tensor
out = enzyme("test.c", “f").apply(inp)

# Derive gradient
out.backward()
print(inp.grad)
```

```python
import tensorflow as tf
from tf_enzyme import enzyme

inp = tf.Variable(…)
# Use external C code as a regular TF op

out = enzyme(inp, filename=“test.c",
             function=“f”)

# Results is a TF tensor
out = tf.sigmoid(out)
```

```c
// Input tensor + size, and output tensor
void f(float* inp, size_t n, float* out);

// diffe_dupnoneed specifies not recomputing the output
void diffef(float* inp, float* d_inp, size_t n, float* d_out) {
  __enzyme_autodiff(f, diffe_dup, inp, d_inp, n, diffe_dupnoneed, (float*)0, d_out);
}
```

What is LLVM

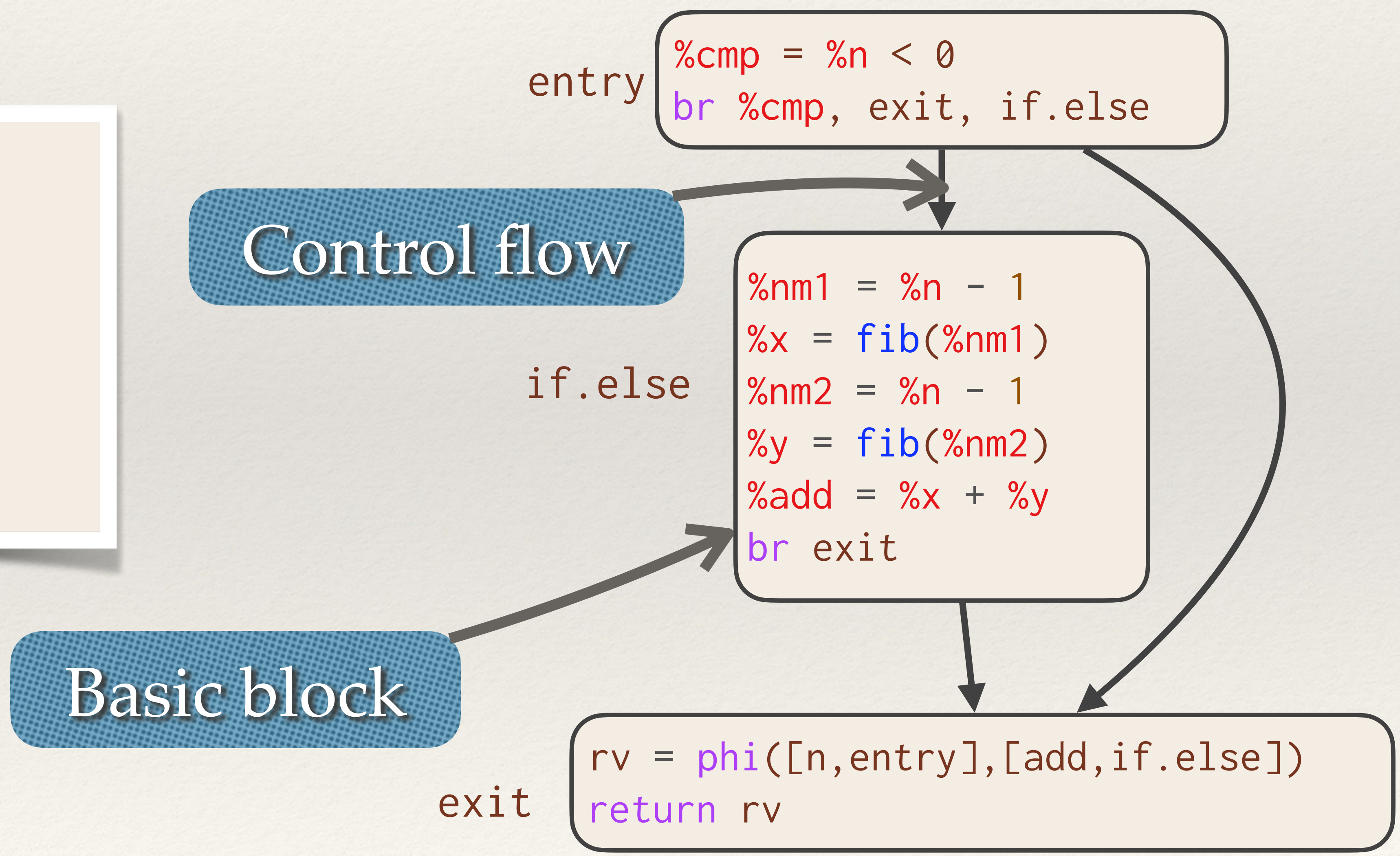
- Generic low-level compiler infrastructure
  - “Cross platform assembly”
- Goal: efficient compilation of arbitrary code
  - Well-defined semantics
  - Large collection of optimization and analysis passes for handling



LLVM IR

LLVM represents each function as a **control-flow graph (CFG)** of **BasicBlocks**, containing lists of **Instructions**.

```c
int fib(int n) {
  if (n < 2) return n;
  int x, y;
  x = fib(n - 1);
  y = fib(n - 2);
  return x + y;
}
```



Core Algorithm

- Type Analysis
- Activity Analysis
- Synthesize derivatives
  - Forward pass that mirrors original code
  - Reverse pass inverts instructions in forward pass (adjoints)
- Optimize

The "memcpy" Problem

- Taking the derivative of operations such as memcpy memcpy depends on the type of the data being copied
  - e.g. one derivative for pointers, one for doubles, another for floats
- LLVM Types != C/C++ types

```
void f(void* dst, void* src) {
  memcpy(dst, src, 8);
}
```

```
void
grad_f(double* dst, double* dst',
       double* src, double* src') {
  // Forward Pass
  memcpy(dst, src, 8);

  // Reverse Pass
  src'[0] += dst'[0];
  dst'[0] = 0;
}
```

```
void
grad_f(float* dst, float* dst',
       float* src, float* src') {
  // Forward Pass
  memcpy(dst, src, 8);

  // Reverse Pass
  src'[0] += dst'[0];
  dst'[0] = 0;
  src'[1] += dst'[1];
  dst'[1] = 0;
}
```

Type Analysis

- New interprocedural dataflow analysis that detects the underlying type of data
- Each value has a set of memory offsets : type

```
x = {[]:Pointer, [0]:Double, [8]:Pointer, [8,0]:Integer}
```

```
struct Type {
  double;
  int*;
}
```

```
x = Type*;
```

Type Analysis

- Initialize type trees for values from constant, TBAA, and known instruction information
- Each instruction has a type propagation rule describing how types flow through
- Perform series of fixed-point updates propagating type information to uses/users
- Provide a compile-time error if a necessary type cannot be deduced statically

Activity Analysis

- Determines what instructions could impact derivative computation
- Avoids taking meaningless or unnecessary derivatives (e.g. d/dx cpuid)
- Instruction is active iff it can propagate a differential value to its return or memory
- Build off of alias analysis & type analysis
  - E.g. all read-only function that returns an integer are inactive since they cannot propagate adjoints through the return or to any memory location

Shadow Memory

- Derivatives of values are stored in shadow allocations
- For all active values, allocate and zero shadow memory to store the derivative of all of its occurrences
- All data structures need to have a shadow data structure created
    - Enzyme will create shadow allocation/stores for structures created inside code being differentiated
    - Data structures passed as arguments will pass shadow arguments

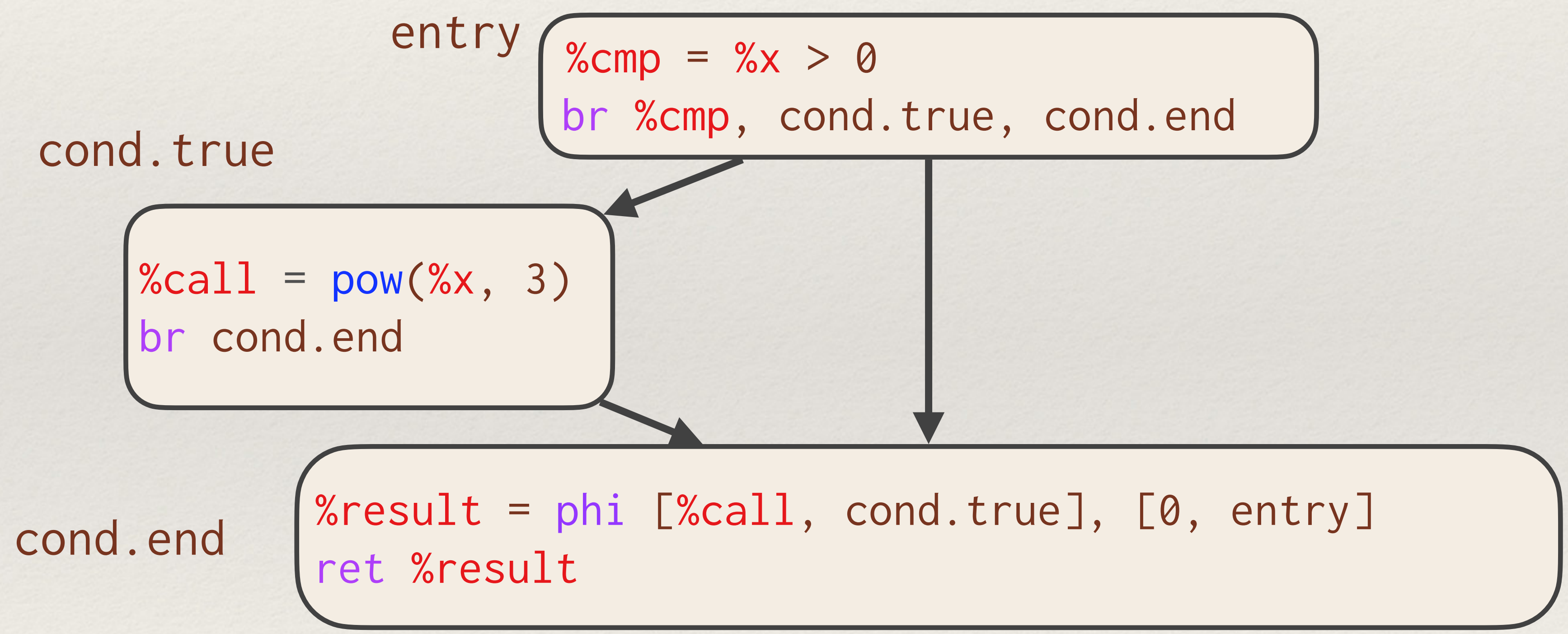
Derivative Synthesis

- Initialize shadow memory
- For each BasicBlock BB:
  - For each Instruction I in reverse(BB):
    - Emit adjoint I, caching and reloading any necessary values from the forward pass

Case Study: ReLU3

```
define double @relu3(double %x)
```

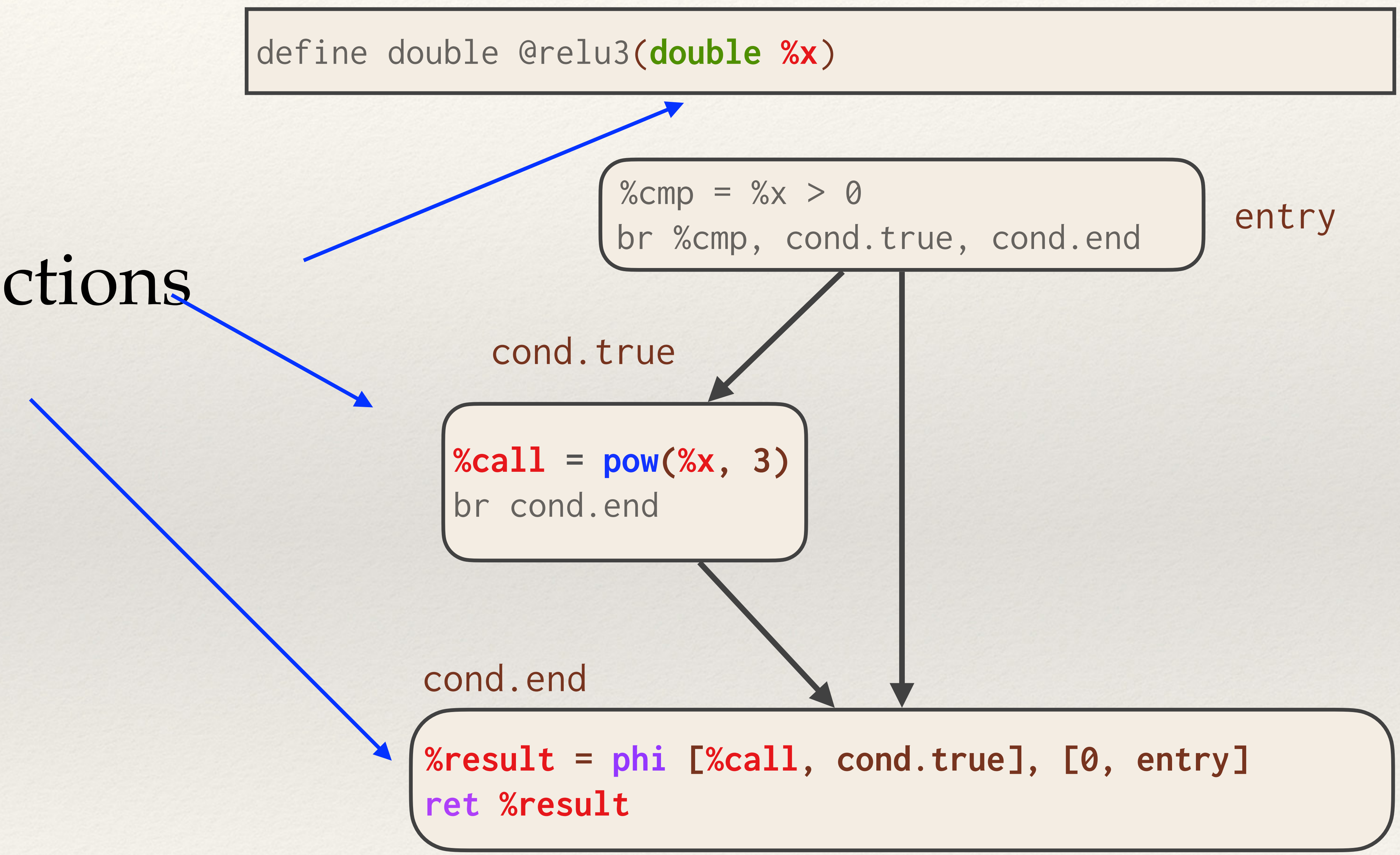
```c
double relu3(double x) {
  double result;
  if (x > 0)
    result = pow(x, 3);
  else
    result = 0;
  return result;
}
```




```c
double diffe_relu3(double x) {
  return __enzyme_autodiff(relu3, x);
}
```

Case Study: ReLU-f

Active Instructions



```
define double @diffe_relu3(double %x, double %differet)
```

entry

```
alloca %result' = 0.0
alloca %call'   = 0.0
alloca %x'      = 0.0
%cmp = %x > 0
br %cmp, cond.true, cond.end
```

Allocate & zero shadow memory for active instructions

cond.true

```
%call = pow(%x, 3)
br cond.end
```

cond.end

```
%result = phi [%call, cond.true], [0, entry]

; deleted return

%result' = 1.0
br reverse_cond.end
```

```
define double @diffe_relu3(double %x, double %differet)
```

Compute adjoints for active instructions

entry

```
alloca %result' = 0.0
alloca %call'   = 0.0
alloca %x'      = 0.0
%cmp = %x > 0
br %cmp, cond.true, cond.end
```

cond.true

```
%call = pow(%x, 3)
br cond.end
```

cond.end

```
%result = phi [%call, cond.true], [0, entry]

; deleted return

%result' = 1.0
br reverse_cond.end
```

reverse_cond.true

```
%df = 3 *pow(%x, 2)
%tmp_call' = load %call
%x' += %df * %tmp_call'
store %call' = 0.0
br reverse_entry
```

reverse_cond.end

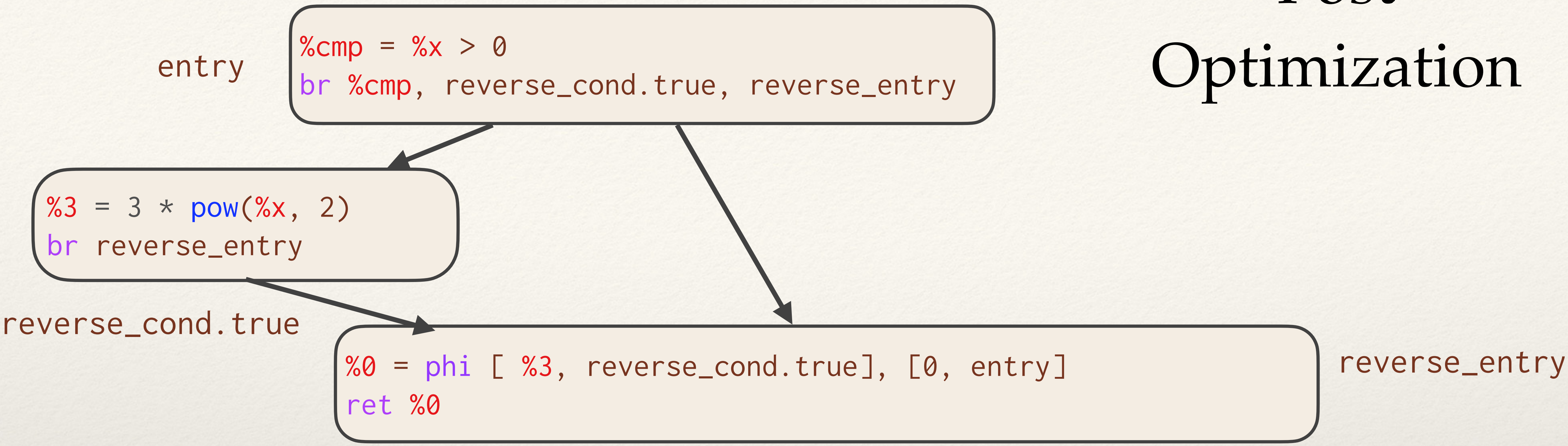
```
%tmp_res' = load %result'
%call' += if %x > 0 then %tmp_res' else 0
store %result' = 0.0
br %cmp, reverse_cond.true, reverse_entry
```

reverse_entry

```
%0 = load %x'
ret %0
```

Post Optimization

```
define double @diffe_relu3(double %x)
```



Essentially the optimal hand-compiled program!

```c
double diffe_relu3(double x) {
  double result;
  if (x > 0)
    result = 3 * pow(x, 2);
  else
    result = 0;
  return result;
}
```

Cache

- Adjoint instructions may require values from the forward pass
  - e.g. $\nabla(x * y) \Rightarrow x\,dy + y\,dx$
- For all such values, allocate memory in the function header to store the value for use in the reverse pass
- Values computed inside loops are stored in an array indexed by the loop induction variable
  - Array allocated statically if possible; otherwise dynamically `realloc`'d

Case Study: Read Sum

```c
double sum(double* x) {
  double total = 0;

  for(int i=0; i<10; i++)
    total += read() * x[i];

  return total;
}
```

```c
void diffe_sum(double* x,
                 double* xp) {
  return
   __enzyme_autodiff(sum, x, xp);
}
```

```llvm
define double @sum(double* %x)
```

entry

```llvm
br for.body
```

for.body

```llvm
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
%0 = load %x[%i]
%mul = %0 * %call
%add = %mul + %total
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, for.cleanup, for.body
```

for.cleanup

```llvm
%result = phi [ %call, cond.true], [0, entry]
ret %result
```

Case Study: Read Sum

```
define double @sum(double* %x)
```

Active Variables

entry

```
br for.body
```

for.body

```
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
%0 = load %x[%i]
%mul = %0 * %call
%add = %mul + %total
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, for.cleanup, for.body
```

for.cleanup

```
%result = phi [%call, cond.true], [0, entry]
ret %result
```

Case Study: Read Sum

Each register in the for loop represents a distinct active variable every iteration

```
define double @sum(double* %x)
```

entry

```
br for.body
```

for.body

```
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
%0 = load %x[%i]
%mul = %0 * %call
%add = %mul + %total
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, for.cleanup, for.body
```

for.cleanup

```
%result = phi [%call, cond.true], [0, entry]
ret %result
```

```
define double @diffe_sum(double* %x, double* %xp)
```

entry

```
alloca %x'      = 0.0
alloca %total'  = 0.0
alloca %0'      = 0.0
alloca %mul'    = 0.0
alloca %add'    = 0.0
alloca %result' = 0.0

br for.body
```

Allocate & zero shadow memory per active value

for.body

```
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
%0 = load %x[%i]
%mul = %0 * %call
%add = %mul + %total
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, for.cleanup, for.body
```

for.cleanup

```
%result = phi [ %call, cond.true], [0, entry]
ret %result
```

```
define double @diffe_sum(double* %x, double* %xp)
```

Cache forward pass variables for use in reverse

entry

```
alloca %x'      = 0.0
alloca %total'  = 0.0
alloca %0'      = 0.0
alloca %mul'    = 0.0
alloca %add'    = 0.0
alloca %result' = 0.0
%call_cache = @malloc(10 x double)
br for.body
```

for.body

```
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
store %call_cache[%i] = %call
%0 = load %x[%i]
%mul = %0 * %call
%add = %mul + %total
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, for.cleanup, for.body
```

for.cleanup

```
%result = phi [ %call, cond.true], [0, entry]
@free(%cache)
ret %result
```

After lowering & some optimizations

```
define void @diffe_sum(double* %x, double* %xp)
```

entry

```
%call_cache = @malloc(10 x double)
br for.body
```

for.body

```
%i = phi [ 0, entry ], [ %i.next, for.body ]
%total = phi [ 0.0, %entry ], [ %add, for.body ]
%call = @read()
store %call_cache[%i] = %call
%i.next = %i + 1
%exitcond = %i.next == 10
br %exitcond, reversefor.body, for.body
```

reversefor.body

```
%i' = phi [ 9, for.body ], [ %i’.next, reversefor.body ]
%i’.next = %i' - 1
%cached_read = load %call_cache[%i’]
store %xp[%i’] = %cached_read + %xp[%i’]
%exit2 = %i = 0
br %exitcond, %exit2, reversefor.body
```

exit

```
@free(%cache)
ret
```

Case Study: Read Sum

```
define void @diffe_sum(double* %x, double* %xp)
```

entry

```
%call0 = @read()
store %xp[0] = %call0
%call1 = @read()
store %xp[1] = %call1
%call2 = @read()
store %xp[2] = %call2
%call3 = @read()
store %xp[3] = %call3
%call4 = @read()
store %xp[4] = %call4
%call5 = @read()
store %xp[5] = %call5
%call6 = @read()
store %xp[6] = %call6
%call7 = @read()
store %xp[7] = %call7
%call8 = @read()
store %xp[8] = %call8
%call9 = @read()
store %xp[9] = %call9
ret
```

After more optimizations

```
void diffe_sum(double* x, double* xp) {
   xp[0] = read();
   xp[1] = read();
   xp[2] = read();
   xp[3] = read();
   xp[4] = read();
   xp[5] = read();
   xp[6] = read();
   xp[7] = read();
   xp[8] = read();
   xp[9] = read();
}
```

Cache Optimizations

- By carefully caching in a form LLVM understands, existing optimization passes can optimize the memory away! [*]
- Further optimizations:
  - Use alias analysis to prove that recomputing an instruction is legal
  - Don't cache unnecessary values
  - Don't cache a value that already has already been cached elsewhere

[*] For dynamic loops, requires modification to LLVM memory analyses to understand semantics of `realloc`.

Function Calls

- Computing both forward and reverse pass in the same function allows further optimization and reduces memory usage
  - Enzyme uses Alias Analysis to detect legality of computing forward/reverse pass together
- Otherwise, Enzyme may need to modify forward pass to cache values needed by reverse pass

Indirect Function Calls

- Calls to functions that aren't known at compile time are dealt with by leveraging shadow memory
- The shadow of function pointers is defined to be a global containing the forward and reverse pass
- Thus taking the adjoint of an indirect function call simply requires extracting and calling the corresponding shadow callee

Custom Derivatives & Multisource

- One can specify custom forward/reverse passes of functions by attaching metadata

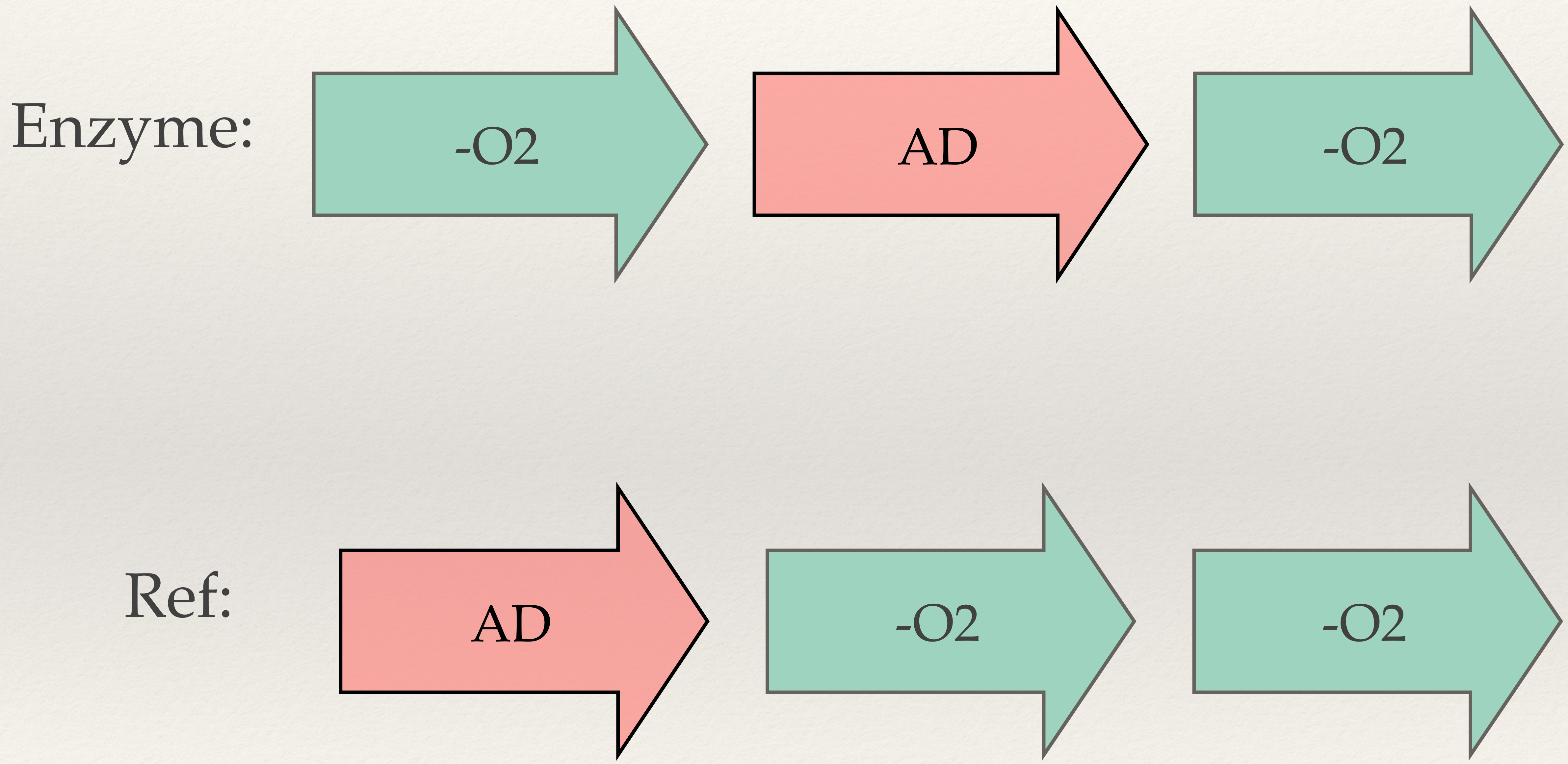
```
__attribute__((enzyme("augment", augment_func)))
__attribute__((enzyme("gradient", gradient_func)))
double func(double n);
```

- Enzyme leverages LLVM's link-time optimization (LTO) & "fat libraries" to ensure that LLVM bitcode is available for all potential differentiated functions before AD

Evaluation

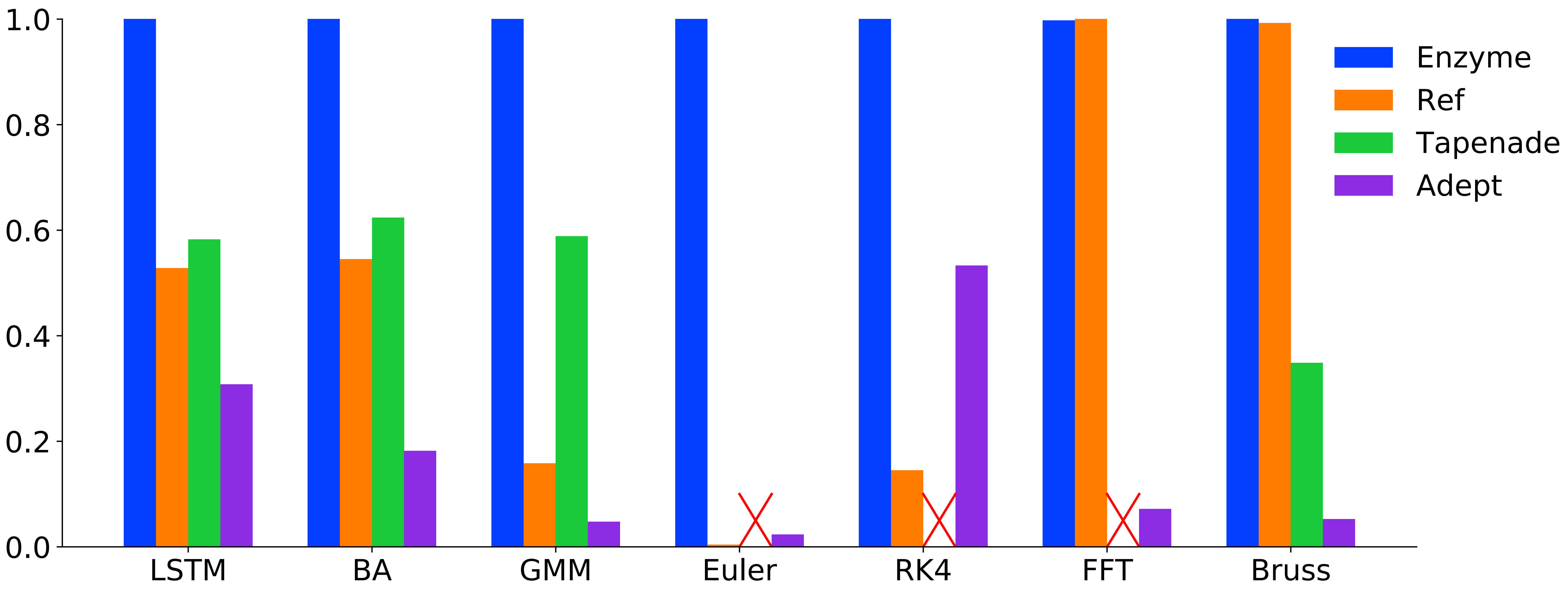
- Collection of benchmarks from Microsoft's ADBench suite and of technically interest
- Evaluated Enzyme, Reference, and the two fastest AD systems from ADBench (Tapenade, Adept)
- All programs run serially
- Quiesed Amazon c4.8xlarge (disabled turbo-boost; hyper-threading)

Reference Pipeline



Relative Speedup

Higher is Better



Speedup of 0.5 denotes program took twice as long as Speedup of 1.0

Runtime

	Enzyme	Ref	Tapenade	Adept
LSTM	**2.353**	4.458	4.042	7.645
BA	**0.424**	0.778	0.680	2.334
GMM	**0.073**	0.462	0.124	1.544
Euler	**0.161**	36.723	nan	6.851
RK4	**3.397**	23.442	nan	6.371
FFT	**0.183**	**0.182**	nan	2.538
Bruss	**0.181**	**0.182**	0.518	3.457

Enzyme is 4.5x faster than Ref!

Conclusions

- AD on low-level IR can be performant
- Optimization before AD is crucial
- Enzyme provides high-performance cross-language AD
- Open-sourcing late summer (email for beta access!)
- Future Work:
    - Parallelism, GPU AD
    - AD-specific optimizations

Acknowledgements

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- The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the United States Air Force or the U.S. Government.

Conclusions

- AD on low-level IR can be performant
- Optimization before AD is crucial
- Enzyme provides high-performance cross-language AD
- Open-sourcing late summer (email for beta access!)
- Future Work:
  - Parallelism, GPU AD
  - AD-specific optimizations

Backup Slides

Type Analysis

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {}
ptr2:     {}
loadtype: {}
ptr3:     {}
cptr2:    {}
notype:   {}
cptr3:    {}
```

ptr2 = indirect

ptr3 = indirect

Load + Store Propagation

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

`callee:`

```
void callee(int* ptr) {
ptr:      {}
ptr2:     {[]:Pointer}
loadtype: {}
ptr3:     {}
cptr2:    {[]:Pointer}
notype:   {}
cptr3:    {[]:Pointer}
```

`ptr2 = indirect`

`ptr3 = indirect`

TBAA Propagation

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {}
ptr2:     {[]:Pointer, [0]:Double}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer}
notype:   {}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr2 = indirect

ptr3 = indirect

cptr3 => ptr

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer}
notype:    {}
cptr3:     {[]:Pointer, [0]:Int}
```

ptr2 = indirect

ptr3 = indirect

ptr => cptr2

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [8]:Int}
notype:   {}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr2 = indirect

ptr3 = indirect

ptr2 Call IPO

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer, [8]:Int}
notype:    {}
cptr3:     {[]:Pointer, [0]:Int}
```

ptr2 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [24]:Int}
idx:     {[]:Int@2}
&x[idx] {}
return  {[]:Pointer, [0]:Double}
```

ptr2 Call IPO - ret

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [8]:Int}
notype:   {}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr2 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [24]:Int}
idx:     {[]:Int@2}
&x[idx] {[]:Pointer, [0]:Double}
return  {[]:Pointer, [0]:Double}
```

ptr2 Call IPO - x

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

```
callee:
```

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [8]:Int}
notype:   {}
cptr3:    {[]:Pointer, [0]:Int}
```

```
ptr2 = indirect
```

```
int* indirect(int* x, int idx) {
x:      {[]:Pointer, [16]:Double, [24]:Int}
idx:    {[]:Int@2}
&x[idx] {[]:Pointer, [0]:Double, [8]:Int}
return  {[]:Pointer, [0]:Double}
```

ptr2 Call IPO - x

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [8]:Int}
notype:   {}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr2 = indirect

```
int* indirect(int* x, int idx) {
x:      {[]:Pointer, [16]:Double, [24]:Int}
idx:    {[]:Int@2}
&x[idx] {[]:Pointer, [0]:Double, [8]:Int}
return  {[]:Pointer, [0]:Double, [8]:Int}
```

ptr2 Call IPO

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [16]:Double, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double, [8]:Int}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer, [8]:Int}
notype:    {}
cptr3:     {[]:Pointer, [0]:Int}
```

ptr2 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@2}
&x[idx] {[]:Pointer, [0]:Double, [8]:Int}
return  {[]:Pointer, [0]:Double, [8]:Int}
```

Requirements & Performance Boosts

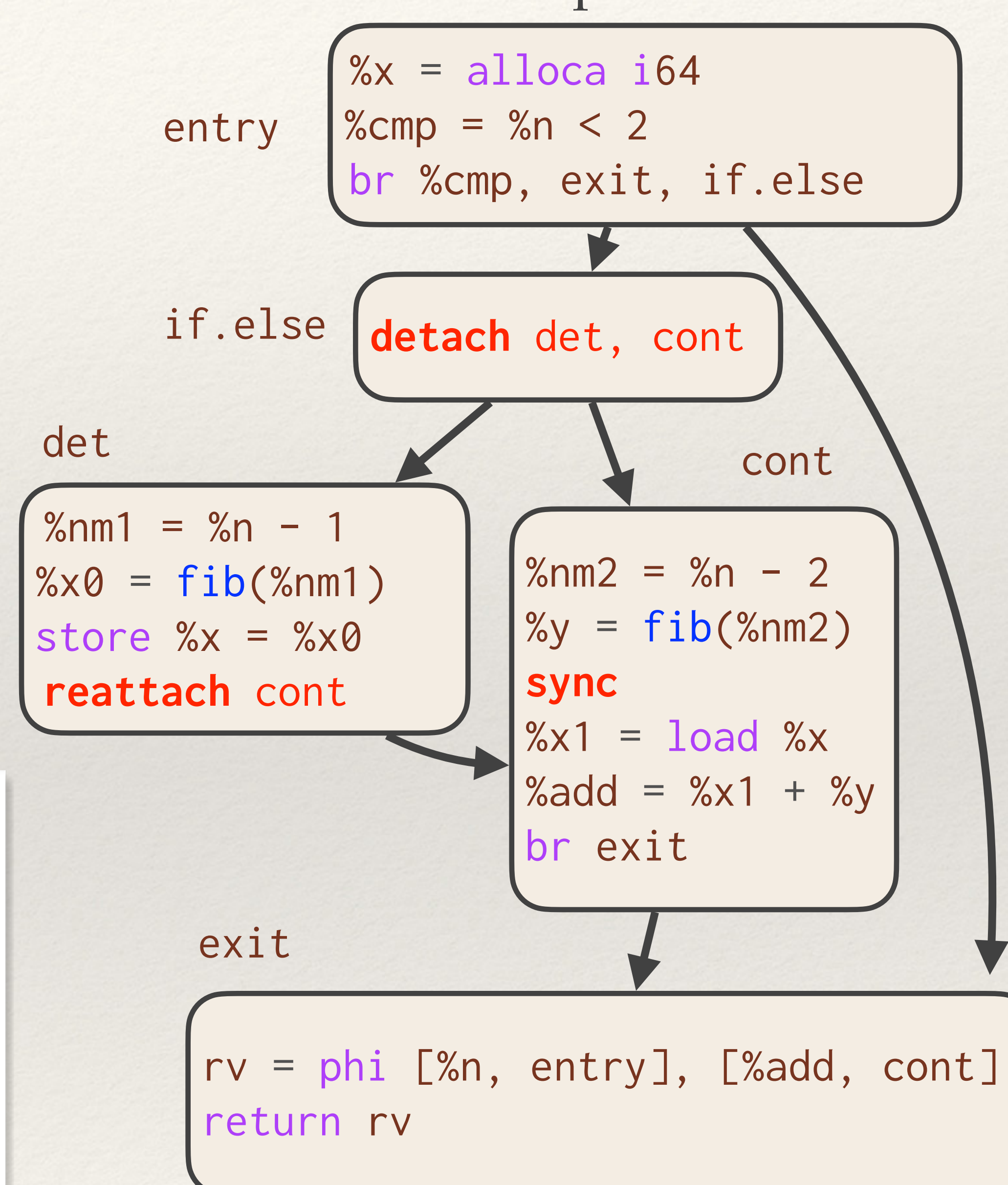
- Requirements
    - Enable TBAA (Type based alias analysis)
    - Strict Aliasing (no unions)
    - Disable exceptions
- Performance Boosts
    - Disable Loop Unrolling before AD
    - Disable Vectorization before AD

Future Work: Parallelism*

- Build off prior work [1] representing parallelism (OpenMP, Cilk, etc) in compiler
- Reverse pass can remain in parallel, with dependencies reversed
- Updates to adjoints in parallel tasks done with reducer or atomic add to prevent races

```c
int fib(int n) {
  if (n < 2) return n;
  int x, y;
  x = spawn fib(n - 1);
  y = fib(n - 2);
  sync;
  return x + y;
}
```

Tapir CFG



[1] Tapir; Tao. B Schardl, **William S Moses**, Charles E. Leiserson; PPoPP 2017

[*] Work in progress — suggestions appreciated

Benchmarks

- LSTM: Long-short term memory model
- BA: Bundle analysis
- GMM: Gaussian mixture model
- Euler: Euler integration
- RK4: Runge-Kutta integration
- FFT: Fast Fourier transform
- Bruss: Brusselrator chemical simulation

Matrix Vector: Single Iteration

```
#define N 20000
#define M 20000
#define ITERS 1
```

	Enzyme	Adept
Normal	1.119	0.0006
Forward	1.119	11.016
Forward +Reverse	1.210	13.445

Taylor Expand Log

```
static adouble logger(adouble x) {
  adouble sum = 0;
  for(int i=1; i<=ITERS; i++) {
    sum += pow(x, i) / i;
  }
  return sum;
}

static double logger_and_gradient(double xin, double& xgrad) {
    adept::Stack stack;
    adouble x = xin;
    stack.new_recording();
    adouble y = logger(x);
    y.set_gradient(1.0);
    stack.compute_adjoint();
    xgrad = x.get_gradient();
    return y.value();
}
```

Taylor Expand Log (Julia)

$$f(x) = \sum_{i=1}^{N} \frac{x^i}{i} \approx -\log(1-x)$$

```c
#define ITERS 10000000
double logger(double x) {
  double sum = 0;

  for(int i=1; i<=ITERS; i++)
    sum += pow(x, i) / i;

  return sum;
}
```

```julia
function jl_f1(f::Float64)
  sum = 0 * f;
  for i = 1:10000000
    sum += f^i / i;
  end
  return sum;
end
```

```
; Enzyme derivative code
@show autodiff(fl_f1, 0.5)
@time autodiff(fl_f1, 0.5)
```

$$\frac{\partial}{\partial x} f(x) \approx \frac{1}{1-x}$$

$$\frac{\partial}{\partial x} f(x=0.5) \approx 2$$

```julia
using Zygote
@show jl_f1‘(0.5)
@time jl_f1‘(0.5)
```

Taylor Expand Log

10000000 iterations

	Enzyme	Adept	Enzyme-Julia	Zygote-Julia	AutoGrad-Julia
Normal	3.74	3.72	3.82	3.82	3.82
Forward	3.74	4.56	3.82	3.82	3.82
Forward +Reverse	3.90	4.65	3.95	44.694	896.30

LogSumExp

```c
#define N 10000000
double logsumexp(double* x, size_t n) {
  double A = 0;
  for(int i=1; i < n; i++) {
    A = max(A, x[i]);
  }
  double sema = 0;
  for(int i=0; i < n; i++) {
    sema += max(x[i] - A);
  }
  return max(sema) + A;
}
```

```julia
function logsumexp(x::Array{Float64,1})
  A = maximum(x)
  ema = exp.(x .- A)
  sema = sum(ema)
  return log(sema) + A
end
```

Taylor Expand Log

10000000 iterations

	Enzyme	Adept
Normal	3.74	3.72
Forward	3.74	4.56
Forward +Reverse	3.90	4.65

LogSumExp

10000000 elements

	Enzyme	Adept
Normal	0.364	0.364
Forward	0.364	2.994
Forward +Reverse	0.605	3.836

Find Matrix by Gradient Descent

	Enzyme	Adept
Forward	4.731	25.606
Gradient Descent	22.672	133.354

Training Simple Neural Network

Enzyme	Adept	Handwritten
73.718	338.097	72.178

Picked first C MNIST Code on Github:

https://github.com/AndrewCarterUK/mnist-neural-network-plain-c

- 1-layer fully connected layer => softmax => cross-entropy loss
- Batch size 100
- 1000 iterations
- Learning rate 0.5

Case Study: Subcall

```
double loadsq(double* x) {
  return x[0] * x[0];
}

void f(double* x) {
  *x = loadsq(x);
}
```

```
define double @loadsq(double* %x)
```

```
entry
  %val = load %x
  %mul = %val * %val
  ret %mul
```

```
define void @f(double* %x)
```

```
entry
  %call = @loadsq(%x)
  store %x = %call
  ret
```

```
void diffe_f(double* x,
                  double* xp) {
  __enzyme_autodiff(f, x, xp);
}
```

```
double loadsq(double* x) {
  return x[0] * x[0];
}

void f(double* x) {
  *x = loadsq(x);
}
```

```
define {double,double} @augment_loadsq(double* %x)
```

```
entry
  %val = load %x
  %mul = %val * %val
  ret {/*return val*/%mul,
       /*cache*/    %val}
```

```
define void @diffe_loadsq(double* %x, double* %x’, double %diffe, double %cache)
```

```
entry
  %val = %cache // cannot reload as x changed
  %mul = %val * %val
  %mul’ = %diffe
  %val’ = 2 * %val * %mul’
  store %x’ += %val’
```

```
define {double,double} @augment_loadsq(double* %x)

entry
  %val = load %x
  %mul = %val * %val
  ret {/*return val*/%mul,
       /*cache*/    %val}
```

```
double loadsq(double* x) {
  return x[0] * x[0];
}

void f(double* x) {
  *x = loadsq(x);
}
```

```
define void @diffe_loadsq(double* %x, double* %x', double %diffe, double %cache)

entry
  %val = %cache // cannot reload as x changed
  %mul = %val * %val
  %mul' = %diffe
  %val' = 2 * %val * %mul'
  store %x' += %val'
```

```
define void @diffe_f(double* %x)

entry
  {%call, %cache} = @augment_loadsq(%x)

  store %x = %call

  %call' = load %x'
  store %x' = 0

  @augment_loadsq(%x, %x', %call', %cache)
  ret
```

```
define {double,double} @augment_loadsq(double* %x)
```

entry

```
%val = load %x
%mul = %val * %val
ret {/*return val*/%mul,
     /*cache*/    %val}
```

```
double loadsq(double* x) {
  return x[0] * x[0];
}

void f(double* x) {
  *x = loadsq(x);
}
```

```
define void @diffe_loadsq(double* %x’, double %diffe, double %cache)
```

entry

```
store %x’ += 2 * %cache * %diffe
```

```
define void @diffe_f(double* %x)
```

entry

```
{%call, %cache} = @augment_loadsq(%x)

store %x = %call

%call’ = load %x’
store %x’ = 0

@augment_loadsq(%x’, %call’, %cache)
ret
```

ptr2 Call IPO

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [16]:Double, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double, [8]:Int}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer, [8]:Int}
notype:    {}
cptr3:     {[]:Pointer, [0]:Int}
```

ptr2 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@2}
&x[idx]  {[]:Pointer, [0]:Double, [8]:Int}
return   {[]:Pointer, [0]:Double, [8]:Int}
```

ptr => cptr2

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [16]:Double, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double, [8]:Int}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer, [0]:Double, [8]:Int}
notype:    {}
cptr3:     {[]:Pointer, [0]:Int}
```

cptr2 => notype

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [16]:Double, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double, [8]:Int}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [0]:Double, [8]:Int}
notype:   {[]:Double}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr3 Call IPO

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

```
callee:
```

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [16]:Double, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double, [8]:Int}
loadtype:  {[]:Double}
ptr3:      {}
cptr2:     {[]:Pointer, [0]:Double, [8]:Int}
notype:    {[]:Double}
cptr3:     {[]:Pointer, [0]:Int}
```

```
ptr3 = indirect
```

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@3}
&x[idx]  {}
return   {}
```

ptr3 Call IPO - x

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [16]:Double, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double, [8]:Int}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [0]:Double, [8]:Int}
notype:   {[]:Double}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr3 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@3}
&x[idx] {[]:Pointer, [0]:Int}
return  {}
```

ptr3 Call IPO - return

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

```
callee:
```

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [16]:Double, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double, [8]:Int}
loadtype: {[]:Double}
ptr3:     {}
cptr2:    {[]:Pointer, [0]:Double, [8]:Int}
notype:   {[]:Double}
cptr3:    {[]:Pointer, [0]:Int}
```

```
ptr3 = indirect
```

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@3}
&x[idx] {[]:Pointer, [0]:Int}
return  {[]:Pointer, [0]:Int}
```

ptr3 Call IPO

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:      {[]:Pointer, [16]:Double, [24]:Int}
ptr2:     {[]:Pointer, [0]:Double, [8]:Int}
loadtype: {[]:Double}
ptr3:     {[]:Pointer, [0]:Int}
cptr2:    {[]:Pointer, [0]:Double, [8]:Int}
notype:   {[]:Double}
cptr3:    {[]:Pointer, [0]:Int}
```

ptr3 = indirect

```
int* indirect(int* x, int idx) {
x:       {[]:Pointer, [16]:Double, [24]:Int}
idx:     {[]:Int@3}
&x[idx] {[]:Pointer, [0]:Int}
return   {[]:Pointer, [0]:Int}
```

Done!

```
int* indirect(int* x, int idx) {
  return &x[idx];
}

void callee(int* ptr) {
  int* ptr2 = indirect(ptr, 2);
  double loadtype = *(double*)ptr2;
  int* ptr3 = indirect(ptr, 3);
  int* cptr2 = &ptr[2];
  int notype = *ctr2;
  int* cptr3 = &ptr[3];
  *((int64_t*)cptr3) = 100;
}
```

callee:

```
void callee(int* ptr) {
ptr:       {[]:Pointer, [16]:Double, [24]:Int}
ptr2:      {[]:Pointer, [0]:Double, [8]:Int}
loadtype:  {[]:Double}
ptr3:      {[]:Pointer, [0]:Int}
cptr2:     {[]:Pointer, [0]:Double, [8]:Int}
notype:    {[]:Double}
cptr3:     {[]:Pointer, [0]:Int}
```