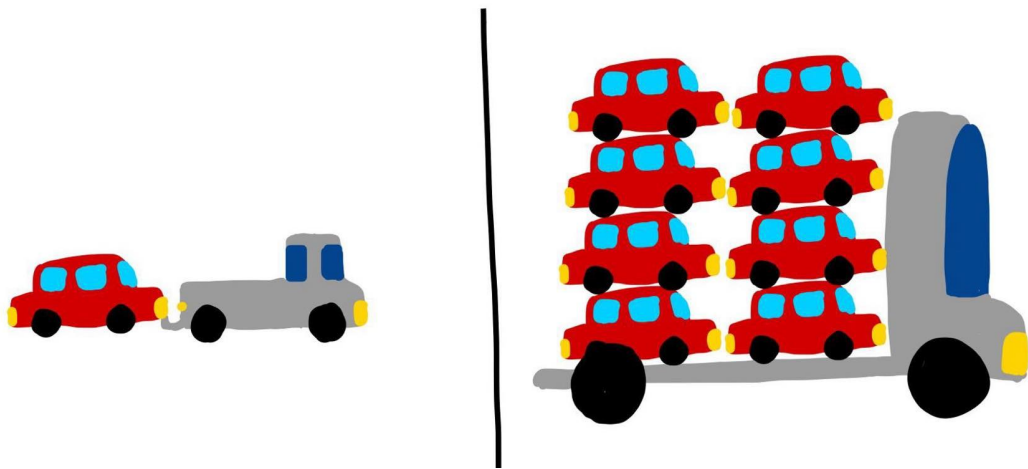


Optimizing optimizers

in PyTorch

Runtime vs memory

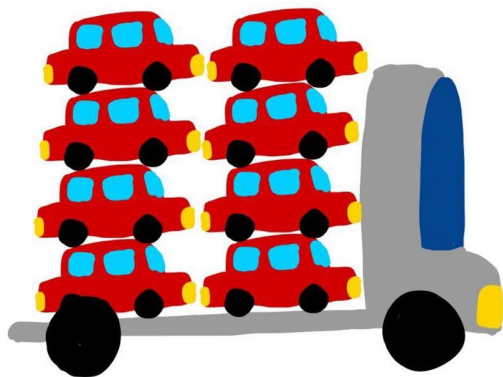
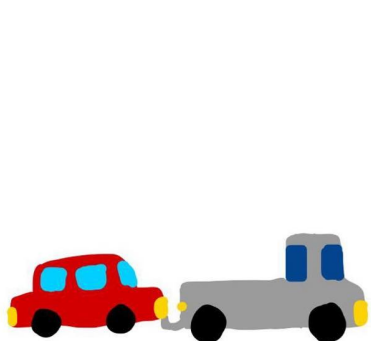
Runtime and memory usage are often at odds with each other



you're towing 512 cars from A to B. which truck do you take?

Runtime vs memory

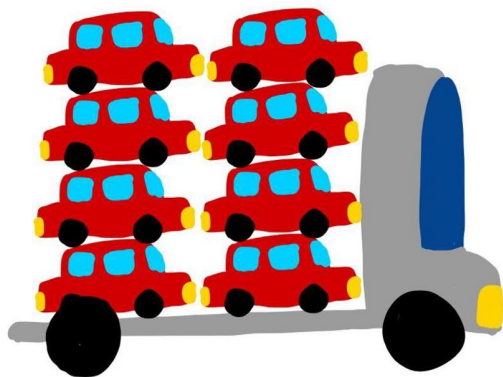
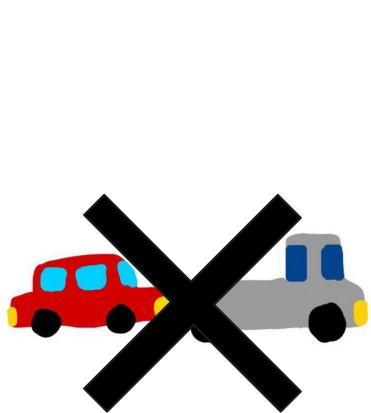
Runtime and memory usage are often at odds with each other



you're towing 512 cars from A to B. which truck do you take?
what if the only way to B had a low clearance bridge?

Runtime vs memory

Runtime and memory usage are often at odds with each other



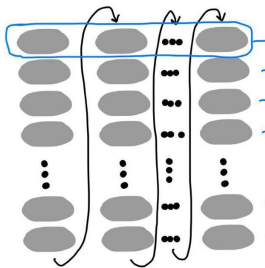
Today, we focus on speeeeeeeeed!

yes this does mean memory will take a hit, disclaimer

Fusion, the high level idea

your simplest optimizer

for loop/single tensor



```
for i, param in enumerate(params):
    grad = grads[i] if not maximize else -grads[i]
    exp_avg = exp_avgs[i]
    exp_avg_sq = exp_avg_sqs[i]
    step_t = state_steps[i]

    # update step
    step_t += 1

    # Perform stepweight decay
    param.mul_(1 - lr * weight_decay)

    # Decay the first and second moment running average coefficient
    exp_avg.lerp_(grad, 1 - beta1)
    exp_avg_sq.mul_(beta2).addcmul_(grad, grad, value=1 - beta2)
    step = _get_value(step_t)

    bias_correction1 = 1 - beta1 ** step
    bias_correction2 = 1 - beta2 ** step

    step_size = lr / bias_correction1

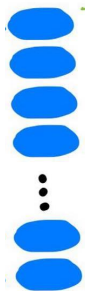
    bias_correction2_sqrt = _dispatch_sqrt(bias_correction2)
    denom = (exp_avg_sq.sqrt() / bias_correction2_sqrt).add_(eps)

    param.addcdiv_(exp_avg, denom, value=-step_size)
```

<https://github.com/pytorch/pytorch/blob/b5ba80828f77c565bcda7558da97c792af32d517/torch/optim/adamw.py#L362>

horizontally fused optimizer

foreach



```
torch._foreach_add_(device_state_steps, 1)

# Perform stepweight decay
if weight_decay != 0:
    torch._foreach_mul_(device_params, 1 - lr * weight_decay)

# Decay the first and second moment running average coefficient
torch._foreach_lerp_(device_exp_avgs, device_grads, 1 - beta1)

torch._foreach_mul_(device_exp_avg_sqs, beta2)
torch._foreach_addcmul_(device_exp_avg_sqs, device_grads,
                        device_grads, 1 - beta2)

...

torch._foreach_div_(exp_avg_sq_sqrt, bias_correction2_sqrt)
torch._foreach_add_(exp_avg_sq_sqrt, eps)
torch._foreach_addcdiv_(device_params, device_exp_avgs,
                        exp_avg_sq_sqrt, step_size)
```

<https://github.com/pytorch/pytorch/blob/b5ba80828f77c565bcda7558da97c792af32d517/torch/optim/adamw.py#L480>

entirely fused optimizer

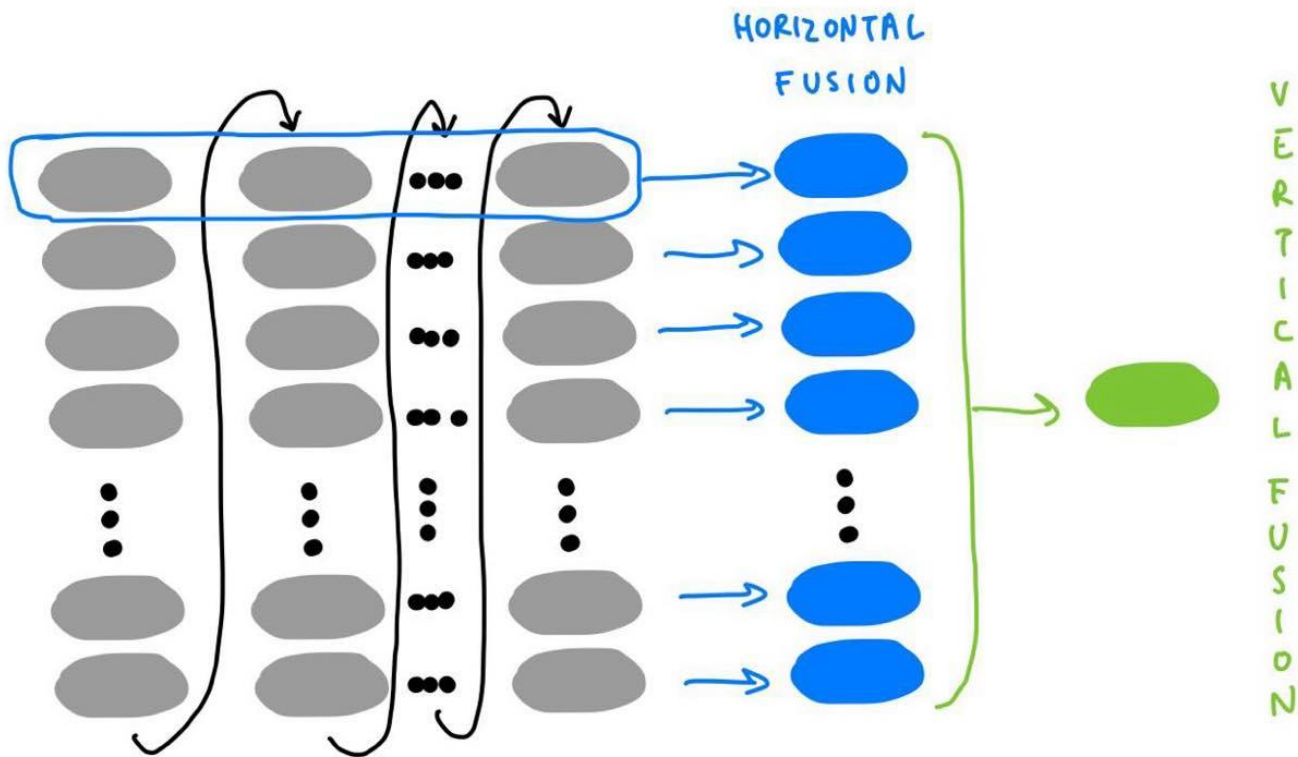
...fused

(thanks NVIDIA)



```
torch._fused_adamw(  
    device_params,  
    device_grads,  
    device_exp_avgs,  
    device_exp_avg_sqs,  
    device_max_exp_avg_sqs,  
    device_state_steps,  
    amsgrad=amsgrad,  
    lr=lr,  
    beta1=beta1,  
    beta2=beta2,  
    weight_decay=weight_decay,  
    eps=eps,  
    maximize=maximize,  
    grad_scale=device_grad_scale,  
    found_inf=device_found_inf,  
)
```


The Gist: the fewer kernels you launch on CUDA, the faster.



Fusion, the nitty gritty

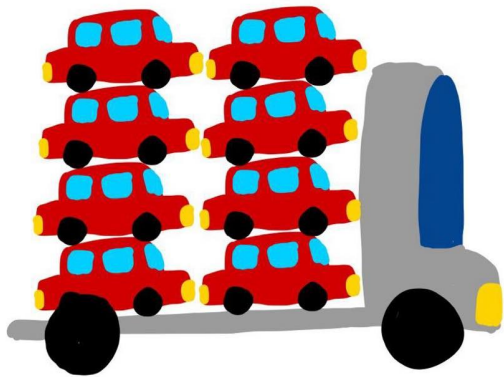
starting with multi_tensor_apply

you know how mitochondria is the powerhouse of the cell?

`multi_tensor_apply` is the powertruck of our speedy optimizers.



CPU



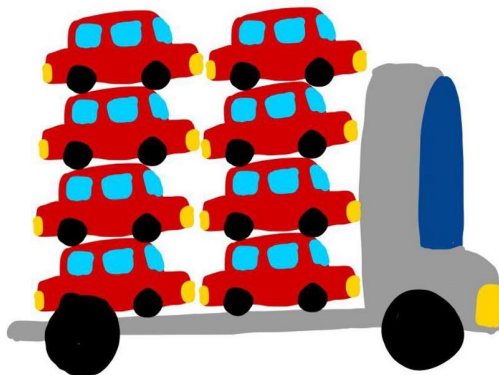
GPU

`multi_tensor_apply` allows us to operate over a list of Tensors vs a single tensor.

Example with torch.add



```
add(  
    Tensor self, Tensor other, *,  
    Scalar alpha=1  
) -> Tensor
```



```
_foreach_add(  
    Tensor[] self, Tensor[] other, *,  
    Scalar alpha=1  
) -> Tensor[]
```

Under the hood in CUDA

`add(Tensor self, Tensor other, *,
Scalar alpha=1) -> Tensor`

A simplified CUDA kernel signature,
assuming we have float Tensors:

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
  
...  
}
```

`_foreach_add(Tensor[] self,
Tensor[] other, *, Scalar alpha=1)
-> Tensor[]`

How would you write this one?

Attempt 1: use std::vector

```
_foreach_add(Tensor[] self, Tensor[] other, *, Scalar alpha=1) -> Tensor[]
```

```
__device__ void _foreach_add_kernel(  
    std::vector<float*> self,  
    std::vector<float*> other,  
    std::vector<float*> res,  
    float alpha=1) {  
    ...  
}
```

Does this work?

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    ...  
}
```

Attempt 1: use std::vector

```
_foreach_add(Tensor[] self, Tensor[] other, *, Scalar alpha=1) -> Tensor[]
```

```
__device__ void _foreach_add_kernel(  
    std::vector<float*> self,  
    std::vector<float*> other,  
    std::vector<float*> res,  
    float alpha=1) {  
    ...  
}
```

Does this work?

No because CUDA doesn't recognize std::vectors!

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    ...  
}
```


Attempt 2: fine i'll use a C-style array then

```
_foreach_add(Tensor[] self, Tensor[] other, *, Scalar alpha=1) -> Tensor[]
```

```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
    ...  
}
```

Does this work?

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    ...  
}
```

Attempt 2: fine i'll use a C-style array then

```
_foreach_add(Tensor[] self, Tensor[] other, *, Scalar alpha=1) -> Tensor[]
```

```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
  
    ...  
}
```

Does this work?

Nope! This will cause an Illegal Memory Access (IMA)
because the outer pointer ***** is a **CPU address**!

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

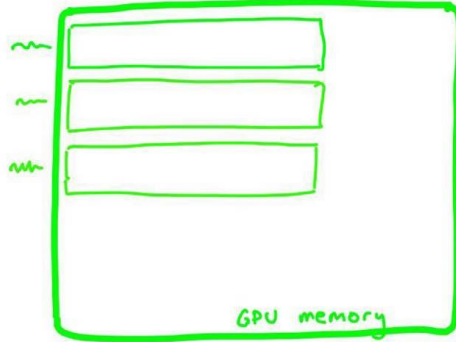
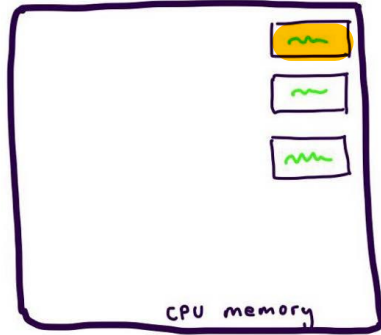
```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
  
    ...  
}
```

Attempt 2: fine i'll use a C-style array then

Look again at the add_kernel.

purple = CPU

green = CUDA/GPU



Tensor data, for a CUDA Tensor



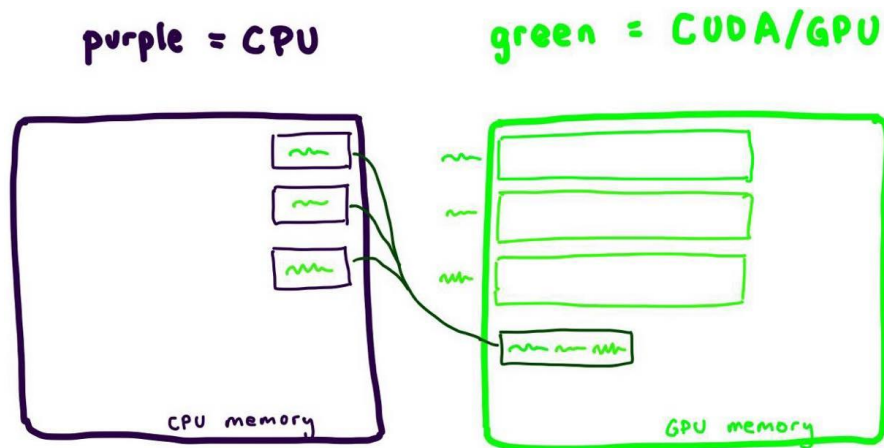
Tensor's data_ptr()

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    ...  
}
```

Attempt 2: fine i'll use a C-style array then

When we dereference in the CUDA kernel, it is OK! The address is in GPU.



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



add_kernel's kernel argument space

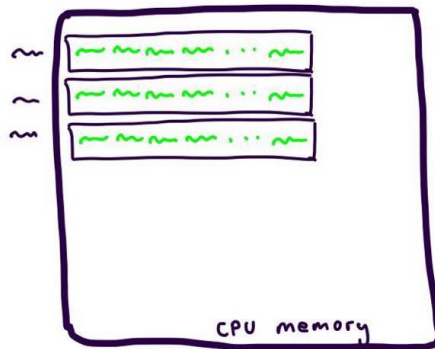
```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor
```

```
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    you're going to dereference in here!  
    ...  
}
```

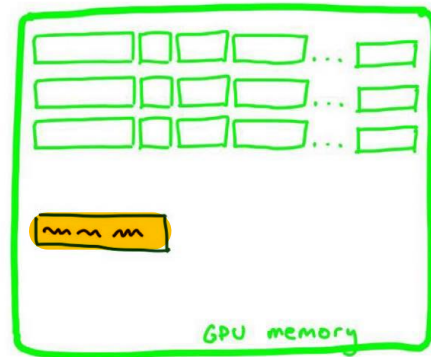
Attempt 2: fine i'll use a C-style array then

```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
    ...  
}
```

purple = CPU



green = CUDA/GPU



But not so our `_foreach_add` kernel.
While Tensors live in GPU, the list part
of TensorLists live in CPU.



Tensor data, for a CUDA Tensor



Tensor's `data_ptr()`



address of the TensorList



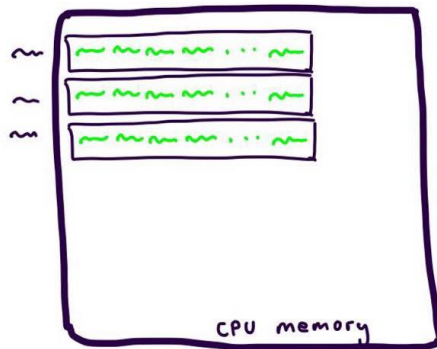
kernel argument space

Attempt 2: fine i'll use a C-style array then

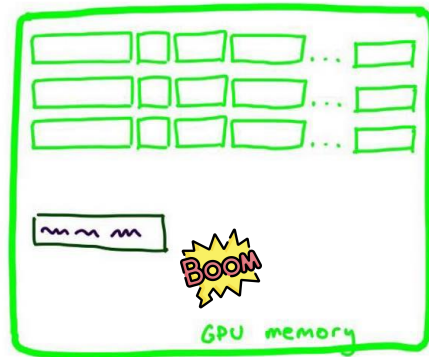
```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
    ...  
}
```

... you're going to dereference in here! **BOOM**

purple = CPU



green = CUDA/GPU



But not so our `_foreach_add` kernel.
While Tensors live in GPU, the list part
of TensorLists live in CPU.

Dereferencing a CPU address from GPU => **BOOM**



Tensor data, for a CUDA Tensor



Tensor's `data_ptr()`



address of the TensorList



kernel argument space

Attempt 3: pass by chonky boi (not reference)

```
struct TensorListMetadata {  
    const float* addresses[3][NUM_TENSORS];  
};
```

<add all the addresses into the struct>

```
__device__ void _foreach_add_kernel(  
    TensorListMetadata tlm,  
    float alpha=1) {  
    ...  
}
```

Does this work?

```
add(Tensor self, Tensor  
other, *, Scalar alpha=1) ->  
Tensor  
  
__device__ void add_kernel(  
    float* self,  
    float* other,  
    float* res,  
    float alpha=1) {  
    ...  
}
```

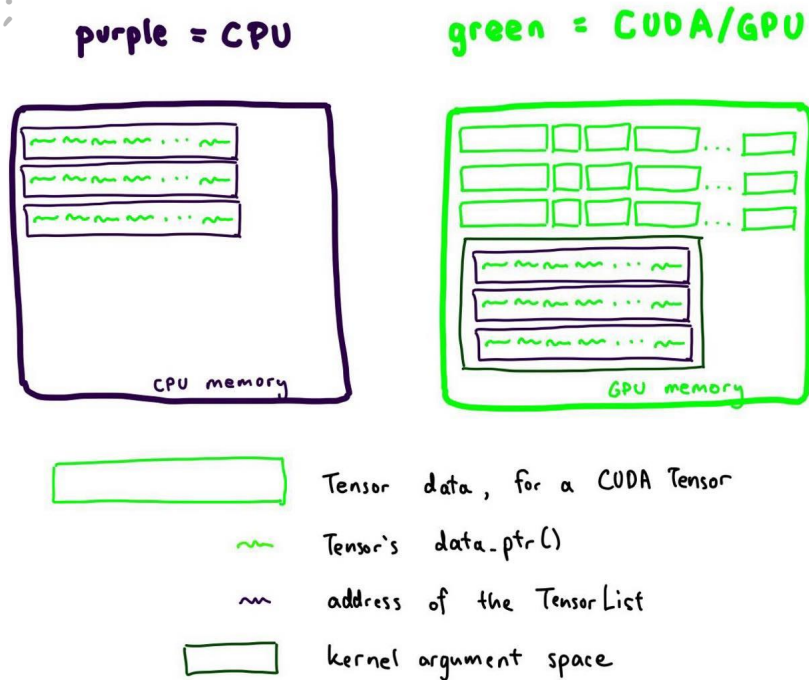
Attempt 3: pass by chonky boi (not reference)

```
struct TensorListMetadata {  
    const float* addresses[3][NUM_TENSORS];  
};
```

<add all the addresses into the struct>

```
__device__ void _foreach_add_kernel(  
    TensorListMetadata tlm,  
    float alpha=1) {  
    ...  
}
```

Does this work? It passes CI! Yay!



~ the end ~

~ the end ~

jk

I actually did land a PR like this and it got reverted :(

Cuz some! how! an illegal memory access happened  for some models (like timm_efficientdet).

I minified the repro to the following and played around with N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

Now would you join me on my (binary) search!

(yes, this example is for norm and not add, but the principle is the same!)

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

N = 412 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

N = 412 

N = 420 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

N = 412 

N = 420 

N = 423 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

N = 412 

N = 420 

N = 423 

N = 424 

Let's binary search over N.

```
params = [torch.rand(2, 3, device="cuda") for _ in range(N)]  
torch._foreach_norm(params, ord=1)  
torch.cuda.synchronize()
```

N = 500 

N = 256 

N = 400 

N = 450 

N = 425 

N = 412 

N = 420 

N = 423 

N = 424 



what is so special about these numbers?
what could be going on here?

Attempt 3: pass by chonky boi (not reference) cont.

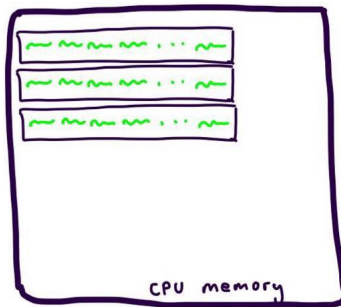
```
struct TensorListMetadata {  
    const float* addresses[3][NUM_TENSORS];  
};
```

<add all the addresses into the struct>

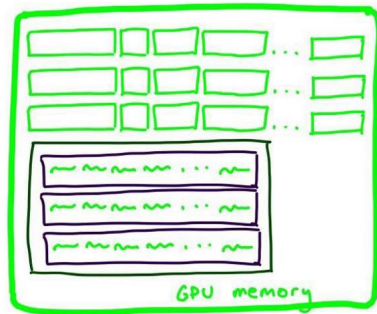
```
__device__ void _foreach_add_kernel(  
    TensorListMetadata tlm,  
    float alpha=1) {  
    ...  
}
```

Does this work? Only if NUM_TENSORS < 424?

purple = CPU



green = CUDA/GPU



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



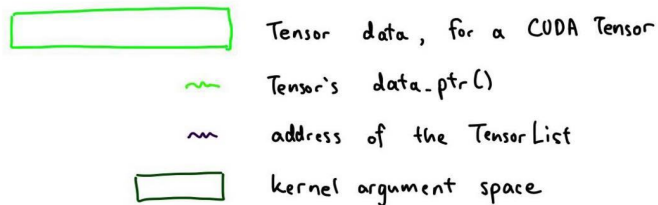
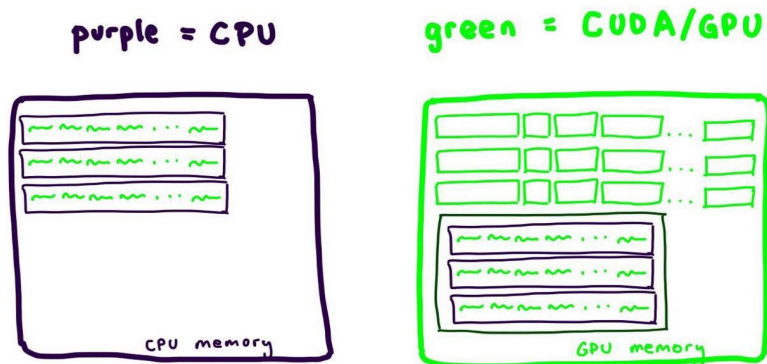
address of the TensorList



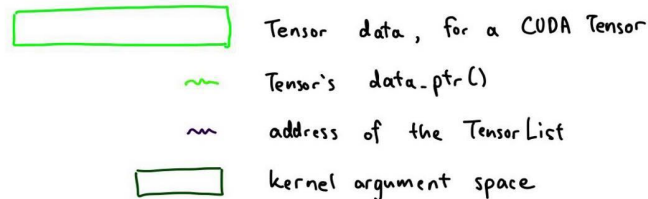
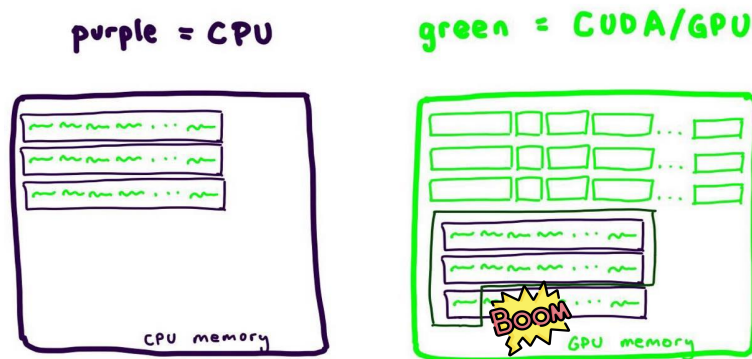
kernel argument space

Attempt 3: pass by chonky boi (not reference) cont.

Expectation:



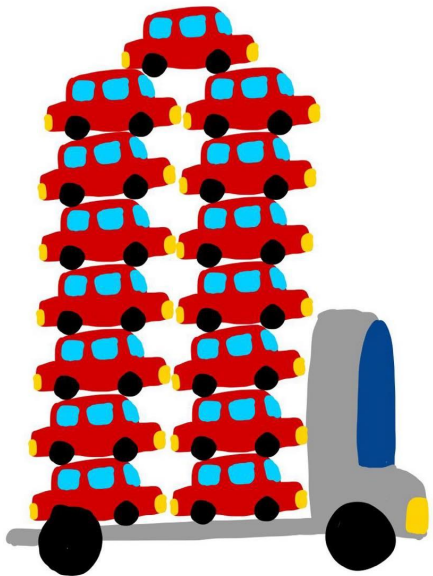
Reality:



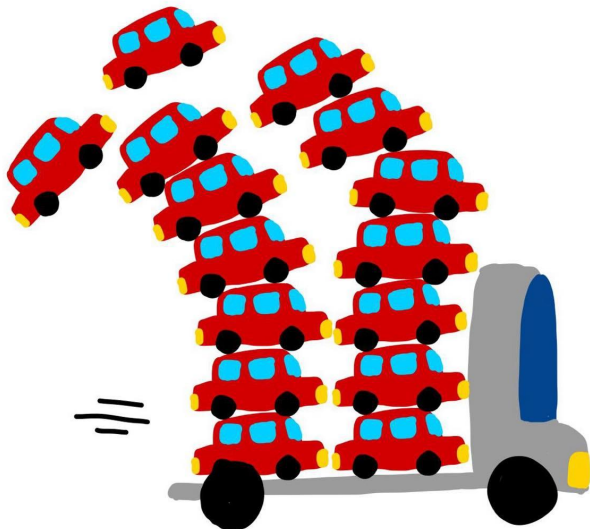
Fun fact: **CUDA Kernel argument space has a max limit of 4KB** 🤔

Attempt 3: pass by chonky boi (not reference) cont.

Expectation:

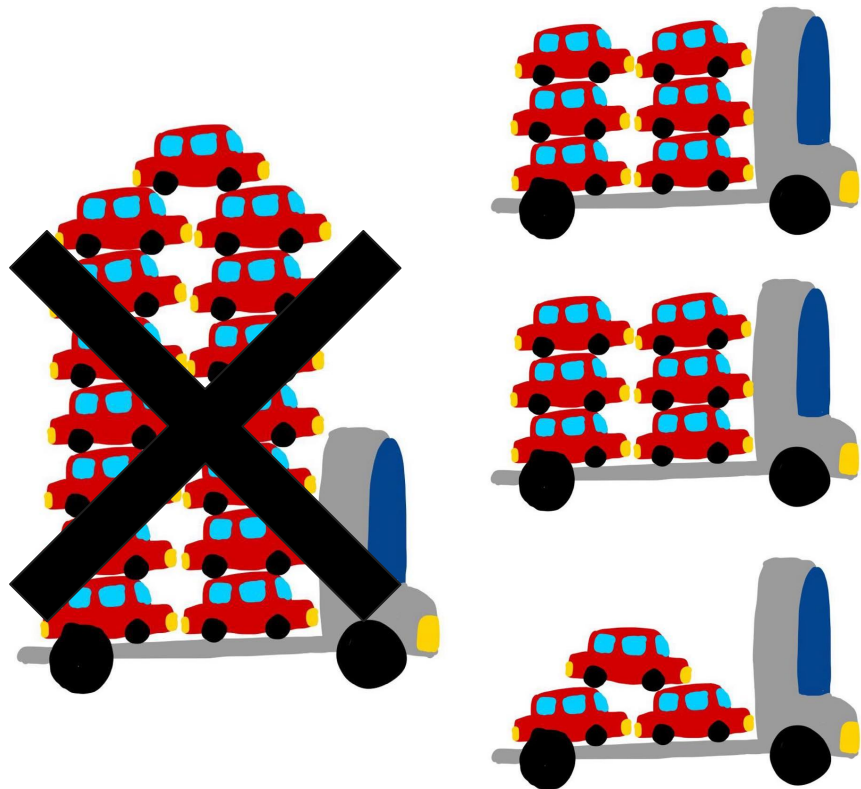


Reality:



Fun fact: CUDA Kernel argument space has a max limit of 4KB 😊 so what now?

Attempt 4: just launch more kernels; make more trips



```
struct TensorListMetadata {  
    const float*  
    addresses[3][MAX_NUM_TENSORS];  
};
```

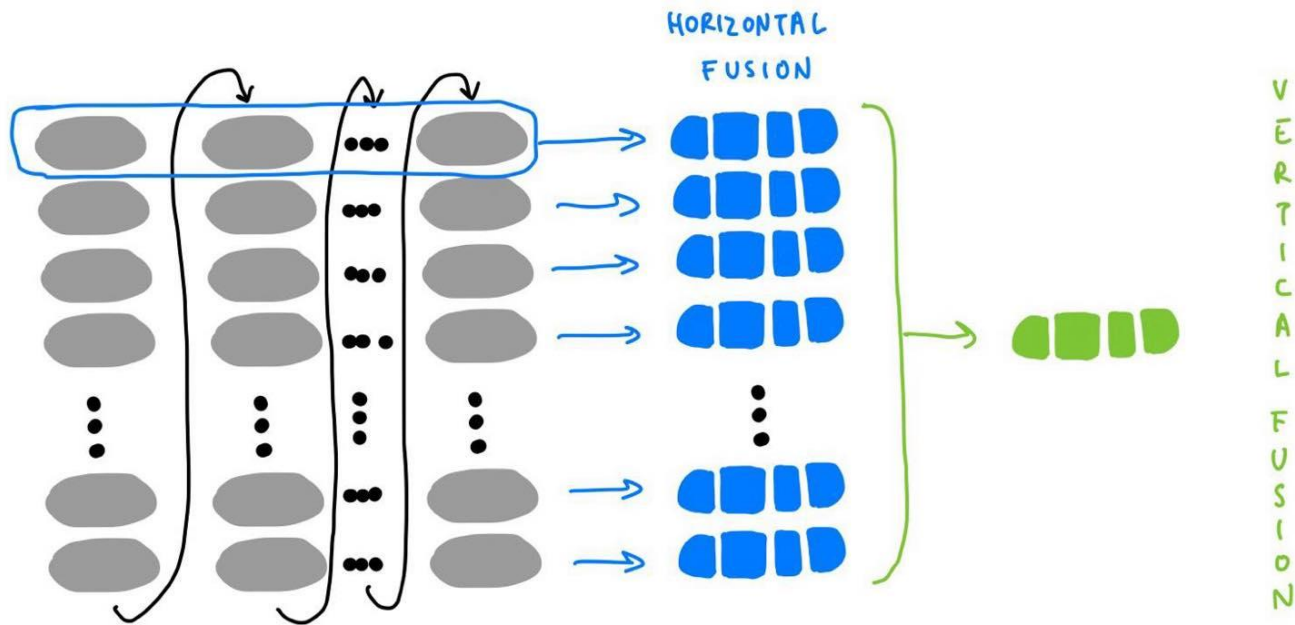
<make multiple structs>
<add a chunk of the addresses to each>
<launch the kernel multiple times>

```
__device__ void _foreach_add_kernel(  
    TensorListMetadata tlm,  
    float alpha=1) {
```

```
...  
}
```

Attempt 4 is what we do today. But we could do better.

While we claim to horizontally fuse into 1 kernel...we often end up with more:



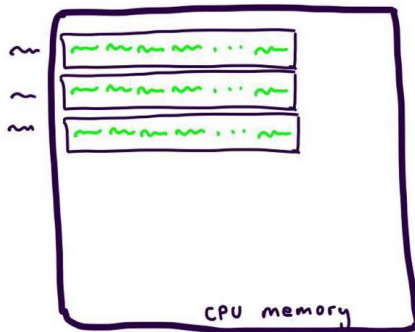
How: revisit attempt 2

```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
    ...  
}
```

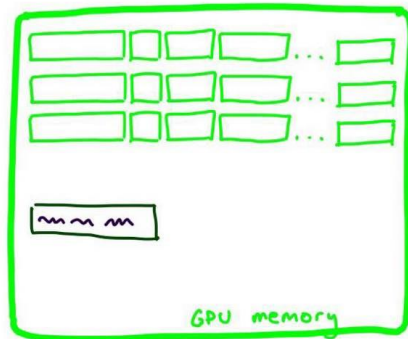
We wanna turn those purple * to green *.

How? **Move them to CUDA beforehand!**
(thanks Yifu Wang!)

purple = CPU



green = CUDA/GPU



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



address of the TensorList



kernel argument space

How: revisit attempt 2

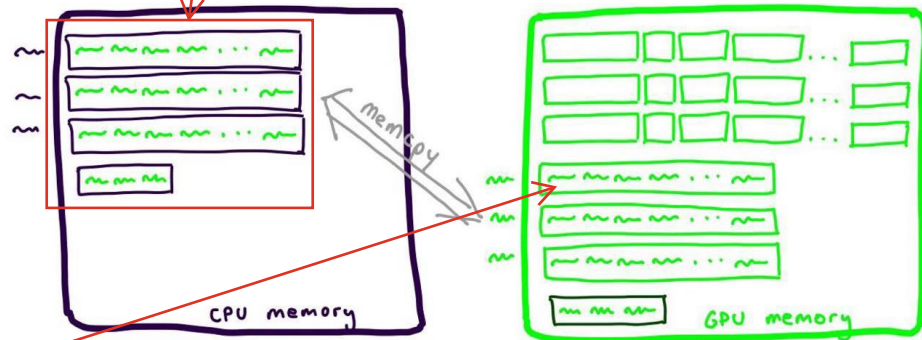
<memcpy the lists of addresses to CUDA>

```
__device__ void _foreach_add_kernel(  
    float** self,  
    float** other,  
    float** res,  
    float alpha=1) {  
    ...  
}
```

Pack all these vectors of pointers
into one tensor, then copy to CUDA

purple = CPU

green = CUDA/GPU



This is now a pointer to
pointer, i.e., float**



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



address of the TensorList



kernel argument space

We thereby avoid the 4KB constraint in the kernel argument to enable launching just one kernel. But remember, memcpy is \$\$\$!

Conclusion: we will be doing a mix of struct + memcpy

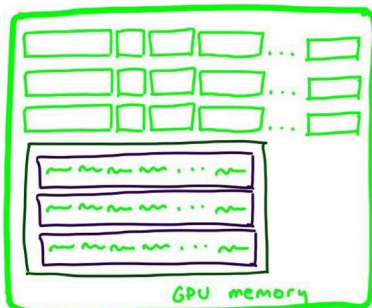
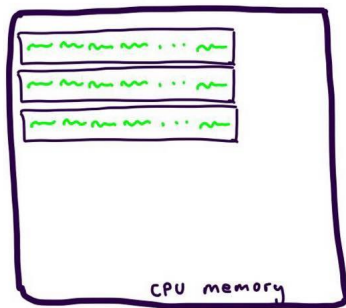
if it fits, use the struct

otherwise, take the memcpy hit

Can we use unified memory here? (currently not supported in PyTorch)

purple = CPU

green = CUDA/GPU



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



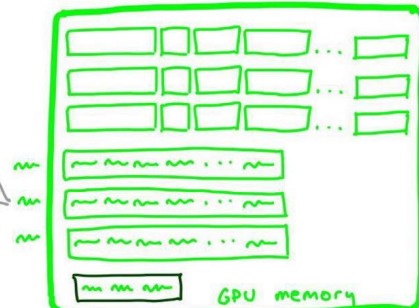
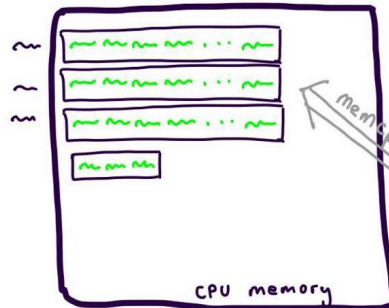
address of the TensorList



kernel argument space

purple = CPU

green = CUDA/GPU



Tensor data, for a CUDA Tensor



Tensor's data_ptr()



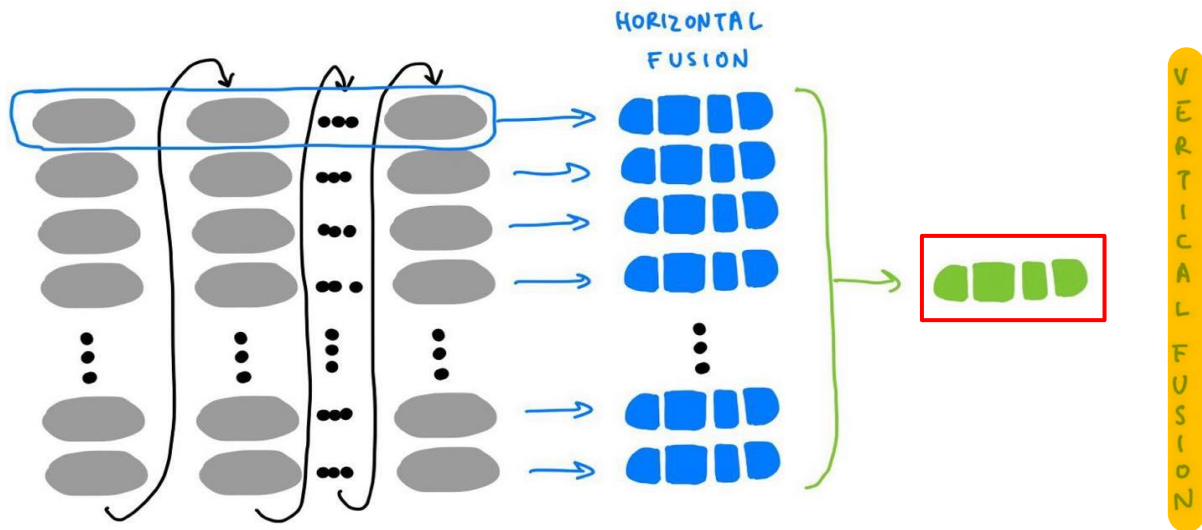
address of the TensorList



kernel argument space

Did you notice I split up the fused implementation too?

This is cuz our fastest fused impls also **rely on multi_tensor_apply!**



Did you notice I split up the fused implementation too?

Whereas `_foreach_add` will call `multi_tensor_apply` with a Callable that does addition, `_fused_adamw` will call `multi_tensor_apply` with a bigger Callable.

```
multi_tensor_apply_kernel<<<  
    loc_block_info,  
    kBlockSize,  
    0,  
    at::cuda::getCurrentCUDAStream()>>>(tensorListMeta, callable, args...);  
C10_CUDA_KERNEL_LAUNCH_CHECK();
```

Did you notice I split up the fused implementation too?

Whereas `_foreach_add` will call `multi_tensor_apply` with a Callable that does addition, `_fused_adamw` will call `multi_tensor_apply` with a bigger Callable.

```
AT_DISPATCH_FLOATING_TYPES_AND2(
    kHalf,
    kBFloat16,
    params[0].scalar_type(),
    "fused_adamw_kernel_cuda",
    [&]() {
        multi_tensor_apply_for_fused_optimizer<4>([
            tensor_lists,
            state_steps,
            FusedAdamMathFunc<scalar_t, 4, ADAM_MODE::ADAMW, false>(),
            lr_ptr,
            1.0, // unused
            beta1,
            beta2,
            weight_decay,
            eps,
            maximize,
            grad_scale_ptr,
            found_inf_ptr];
    });
```


so let's peek at FusedAdamMathFunc

```

struct FusedAdamMathFuncutor {
    C10_DEVICE __forceinline__ void operator()(
        const auto tensor_loc = tl.block_to_tensor[blockIdx.x];
        const auto chunk_idx = tl.block_to_chunk[blockIdx.x];
        const double lr_double = lr_ptr ? *lr_ptr : lr;

        if (found_inf_ptr && *found_inf_ptr == 1) {
            return;
        }

        const auto [bias_correction1: <dependent type>, bias_correction2_sqrt: <dependent type>] =
            [&]() -> std::pair<double, double> {
                auto* step_count: const float * =
                    reinterpret_cast<const float*>[tl.state_steps_addresses[tensor_loc]];
                const auto bias_correction1: double const = 1 - at::native::pow_(base: beta1, exp: *step_count);
                const auto bias_correction2: double const = 1 - at::native::pow_(base: beta2, exp: *step_count);
                const auto bias_correction2_sqrt: const double = std::sqrt(x: bias_correction2);
                return {a: bias_correction1, b: bias_correction2_sqrt};
            }();

        scalar_type* args[depth];
        scalar_type r_args[depth][KILP];
        const auto n = tl.numel_for_tensor[tensor_loc] - chunk_idx * chunk_size;

        const bool all_aligned{
            init_args<depth>(args, tl, chunk_idx, chunk_size, tensor_loc)};
        if ((n % KILP == 0) && (chunk_size % KILP == 0) && all_aligned) {
            for (int64_t i_start = threadIdx.x;
                i_start * KILP < n && i_start * KILP < chunk_size;
                i_start += blockDim.x) {
                #pragma unroll
                for (int i = 0; i < depth; i++) {
                    load_store(dst: r_args[i], src: args[i], dst_offset: 0, src_offset: i_start);
                }
                adam_math<scalar_type, opmath_t, depth, adam_mode, amsgrad>(
                    r_args,
                    lr: lr_double,

```

Locate the thread

```

C10_DEVICE inline void adam_math(
    #pragma unroll
    for (int ii = 0; ii < KILP; ii++) {
        // Load values.
        opmath_t param = static_cast<opmath_t>(r_args[kParamIdx][ii]);
        opmath_t grad = static_cast<opmath_t>(r_args[kGradIdx][ii]);
        if (grad_scale_ptr) {
            grad /= (static_cast<double>(*grad_scale_ptr));
        }
        const opmath_t grad_to_store = grad;
        if (maximize) {
            grad = -grad;
        }
        opmath_t exp_avg = static_cast<opmath_t>(r_args[kExpAvgIdx][ii]);
        opmath_t exp_avg_sq = static_cast<opmath_t>(r_args[kExpAvgSqIdx][ii]);
        opmath_t max_exp_avg_sq;
        if (amsgrad) {
            max_exp_avg_sq = static_cast<opmath_t>(r_args[kMaxExpAvgSqIdx][ii]);
        }
        // Update param, grad, 1st and 2nd order momentum.
        if (weight_decay != 0) {
            if constexpr (adam_mode == ADAM_MODE::ORIGINAL) {
                grad += param * weight_decay;
            } else if constexpr (adam_mode == ADAM_MODE::ADAMW) {
                param -= lr * weight_decay * param;
            }
        }
        // todo(crcrpar): use lerp
        // ref: https://developer.nvidia.com/blog/lerp-faster-cuda/
        exp_avg = beta1 * exp_avg + (1 - beta1) * grad;
        exp_avg_sq = beta2 * exp_avg_sq + (1 - beta2) * grad * grad;
        const opmath_t step_size = lr / bias_correction1;
        opmath_t denom;
        if (amsgrad) {
            max_exp_avg_sq = std::max(max_exp_avg_sq, exp_avg_sq);
            denom = (std::sqrt(max_exp_avg_sq) / bias_correction2_sqrt) + eps;

```

Math part of the optimizer

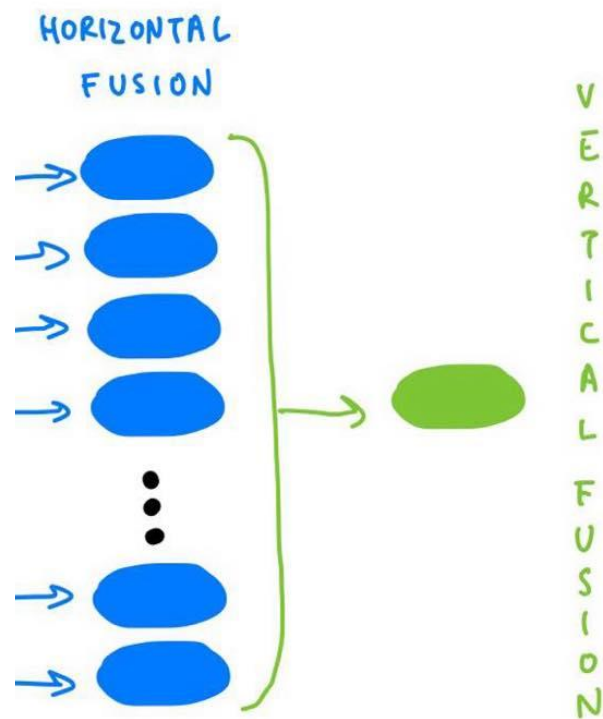
Masak

...that was very manual.

**What if we could automate vertical fusion?
with just 1 line?**

Enter `torch.compile()`

`torch.compile()`'s strength is vertical fusion



How do I use `torch.compile()` with optimizers?

```
optimizer = torch.optim.AdamW(params)
```

```
@torch.compile(fullgraph=False)
def compiled_step():
    optimizer.step()
```

Now call `compiled_step` instead of `optimizer.step()` in your training loop. That's it!

(okay I suppose that was 2 lines)

Inductor will generate a large triton kernel

Use torch.log(...)

```
xpid_offset = xpid - 0
xnumel = 512
xoffset = xpid_offset * XBLOCK
xindex = xoffset + tl.arange(0, XBLOCK)[: ]
xmask = xindex < xnumel
x0 = xindex
tmp0 = tl.load(in_ptr0 + (x0), xmask)
tmp1 = tl.load(in_ptr1 + (x0), xmask)
tmp6 = tl.load(in_ptr2 + (x0), xmask)
tmp13 = tl.load(in_ptr3 + (x0), xmask)
tmp17 = tl.load(in_ptr4 + (0))
tmp18 = tl.broadcast_to(tmp17, [XBLOCK])
tmp2 = tmp1 - tmp0
tmp3 = 0.09999999999999999
tmp4 = tmp2 * tmp3
tmp5 = tmp0 + tmp4
tmp7 = 0.999
tmp8 = tmp6 * tmp7
tmp9 = tmp1 * tmp1
tmp10 = 0.00100000000000000009
tmp11 = tmp9 * tmp10
tmp12 = tmp8 + tmp11
tmp14 = 0.99999
```

```
tmp15 = tmp13 * tmp14
tmp16 = tl.sqrt(tmp12)
tmp19 = tl.math.pow(tmp7, tmp18)
tmp20 = 1.0
tmp21 = tmp19 - tmp20
tmp22 = -tmp21
tmp23 = tl.sqrt(tmp22)
tmp24 = tmp16 / tmp23
tmp25 = 1e-08
tmp26 = tmp24 + tmp25
tmp27 = 0.9
tmp28 = tl.math.pow(tmp27, tmp18)
tmp29 = tmp28 - tmp20
tmp30 = 0.001
tmp31 = tmp29 / tmp30
tmp32 = 1 / tmp31
tmp33 = tmp26 / tmp32
tmp34 = tmp5 / tmp33
tmp35 = tmp15 + tmp34
tl.store(out_ptr0 + (x0), tmp5, xmask)
tl.store(out_ptr3 + (x0), tmp35, xmask)
tl.store(out_ptr4 + (x0), tmp12, xmask)
```


When does it work? (or not work?)

- You must have CUDA capability 7.0+ for Triton
- All optimizers in pytorch/pytorch with a foreach implementation are now compilable
 - So everything except **L-BFGS** and **SparseAdam**
- Vertical fusion of *any* sequence of supported `_foreach_*` ops should work!
 - try out your experimental optimizers!
 - open an issue when this isn't true

Compiled optimizers is in beta! Try it out and complain lots [here](#)!

So should you stop learning CUDA?

So should you stop learning CUDA?

*what about
horizontal
fusion?*

*really knowing
Triton means
knowing CUDA*

*triton isn't
all powerful!*

thanks! questions?