FSDP семинар

Plan

- Prerequisites: CUDA streams / events, DeviceMesh, DTensor
- FSDP2: interface, options, internals
- PyTorch DCP, efficient garbage collection

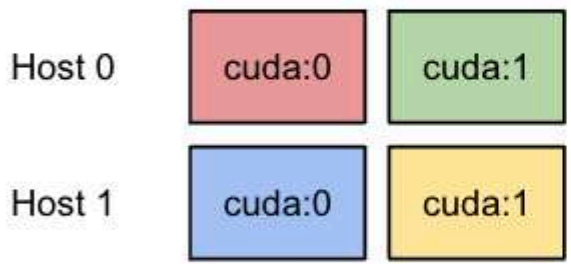
CUDA streams and events

```
all_gather_stream = torch.cuda.Stream()

...

# layer 3 unshard
with torch.cuda.stream(all_gather_stream):
    model.layers[3].all_gather()
    all_gather_event_3 = torch.cuda.Event()
    # or all_gather_stream.record_event()

# layer 2 forward
activations = model.layers[2](activations)

# layer 4 unshard
with torch.cuda.stream(all_gather_stream):
    model.layers[4].all_gather()
    all_gather_event_4 = torch.cuda.Event()

# layer 3 forward
torch.cuda.default_stream().wait_event(all_gather_event_3)
activations = model.block[3](activations)

...
```

CUDA streams and events

DeviceMesh

DeviceMesh: The higher level abstraction that manages ProcessGroups



2 host with 2 GPUs each, represented as a 2-D mesh [[0, 1], [2, 3]]

DeviceMesh

```python
from torch.distributed.device_mesh import init_device_mesh

mesh_1d = init_device_mesh("cuda", mesh_shape=(8,), mesh_dim_names=("dp",))
mesh_2d = init_device_mesh("cpu", mesh_shape=(2, 8), mesh_dim_names=("dp", "tp"))
mesh_3d = init_device_mesh(
    "cuda",
    mesh_shape=(2, 2, 8),
    mesh_dim_names=("pp", "dp", "tp"),
)

dp_group = mesh_2d.get_group("dp")
dist.all_gather( ... , group=dp_group)

mesh_2d.get_local_rank("tp")

mesh_3d["dp", "tp"]._flatten("dp_tp")
```

DTensor

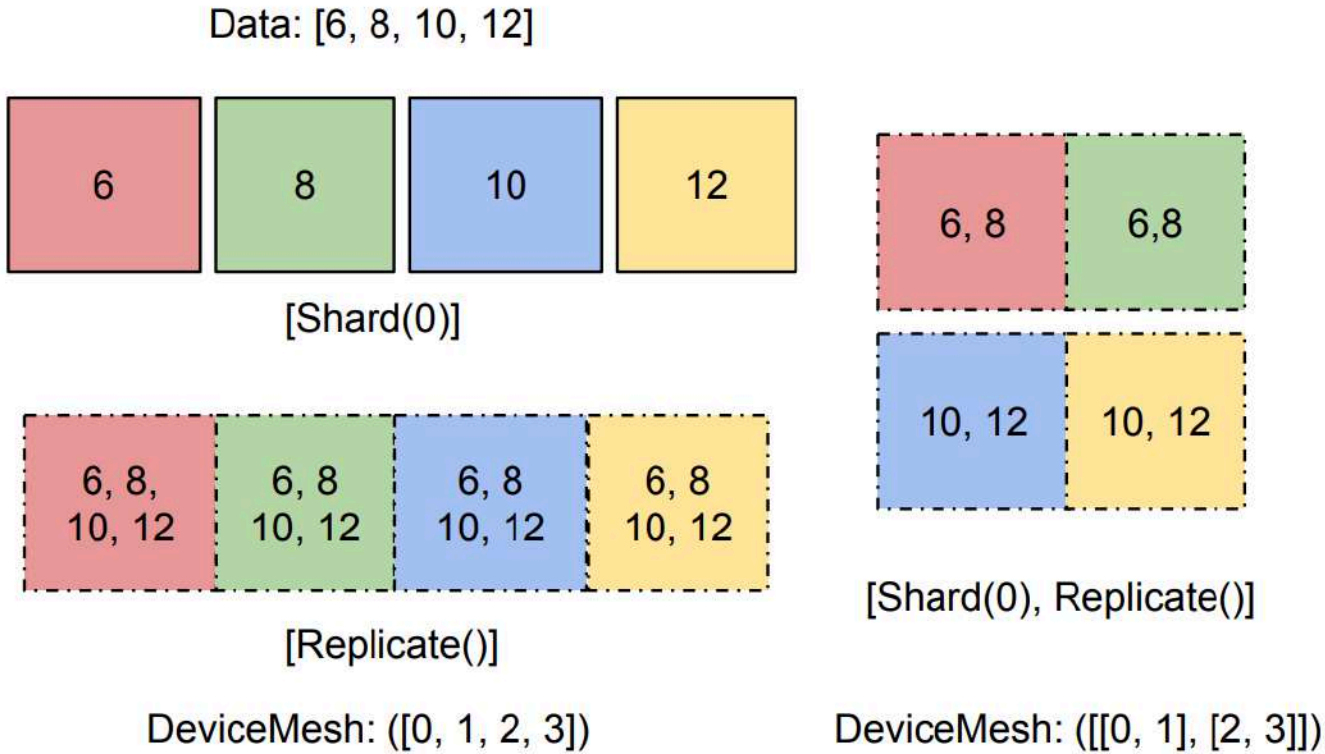
```
from torch.distributed.tensor import DTensor, distribute_tensor

mesh = init_device_mesh("cuda", mesh_shape=(8,), mesh_dim_names=("dp",))
big_tensor = torch.randn(1024, 4096)
placements = (Shard(dim=0),)

dtensor = distribute_tensor(
    big_tensor,
    device_mesh=mesh,
    placements=placements,
)
dtensor._local_tensor
dtensor.to_local() # .shape = (512, 4096)


shard = ... # .shape = (512, 4096)
DTensor.from_local(
    shard,
    device_mesh=mesh,
    placements=placements,
) # .shape = (1024, 4096)

dtensor.redistribute(placements=(Replicate(),))
dtensor.full_tensor()
```

DTensor

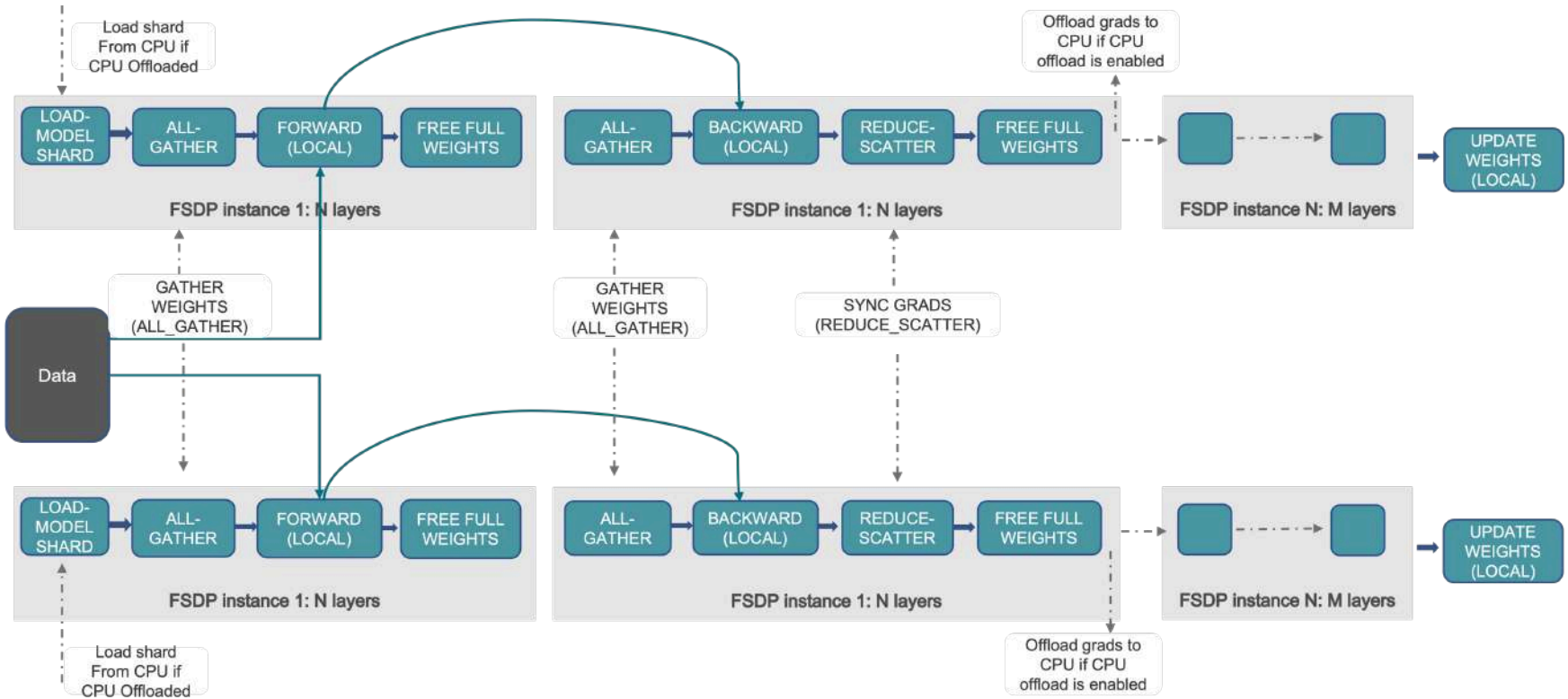
- `Shard`: Tensor sharded on the tensor dimension `dim` on the devices of the `DeviceMesh` dimension
- `Replicate`: Tensor replicated on the devices of the `DeviceMesh` dimension
- `Partial`: Tensor is pending reduction on the devices of the `DeviceMesh` dimension

1. `Shard(dim)` -> `Replicate()`: `all_gather`
2. `Shard(src_dim)` -> `Shard(dst_dim)`: `all_to_all`
3. `Replicate()` -> `Shard(dim)`: local chunking (i.e. `torch.chunk`)
4. `Partial()` -> `Replicate()`: `all_reduce`
5. `Partial()` -> `Shard(dim)`: `reduce_scatter`

DTensor


Data: [6, 8, 10, 12]
6
8
10
12
[Shard(0)]
6, 8,
10, 12
6, 8
10, 12
6, 8
10, 12
6, 8
10, 12
[Replicate()]
DeviceMesh: ([0, 1, 2, 3])
6, 8
6,8
10, 12
10, 12
[Shard(0), Replicate()]
DeviceMesh: ([[0, 1], [2, 3]])

FSDP2

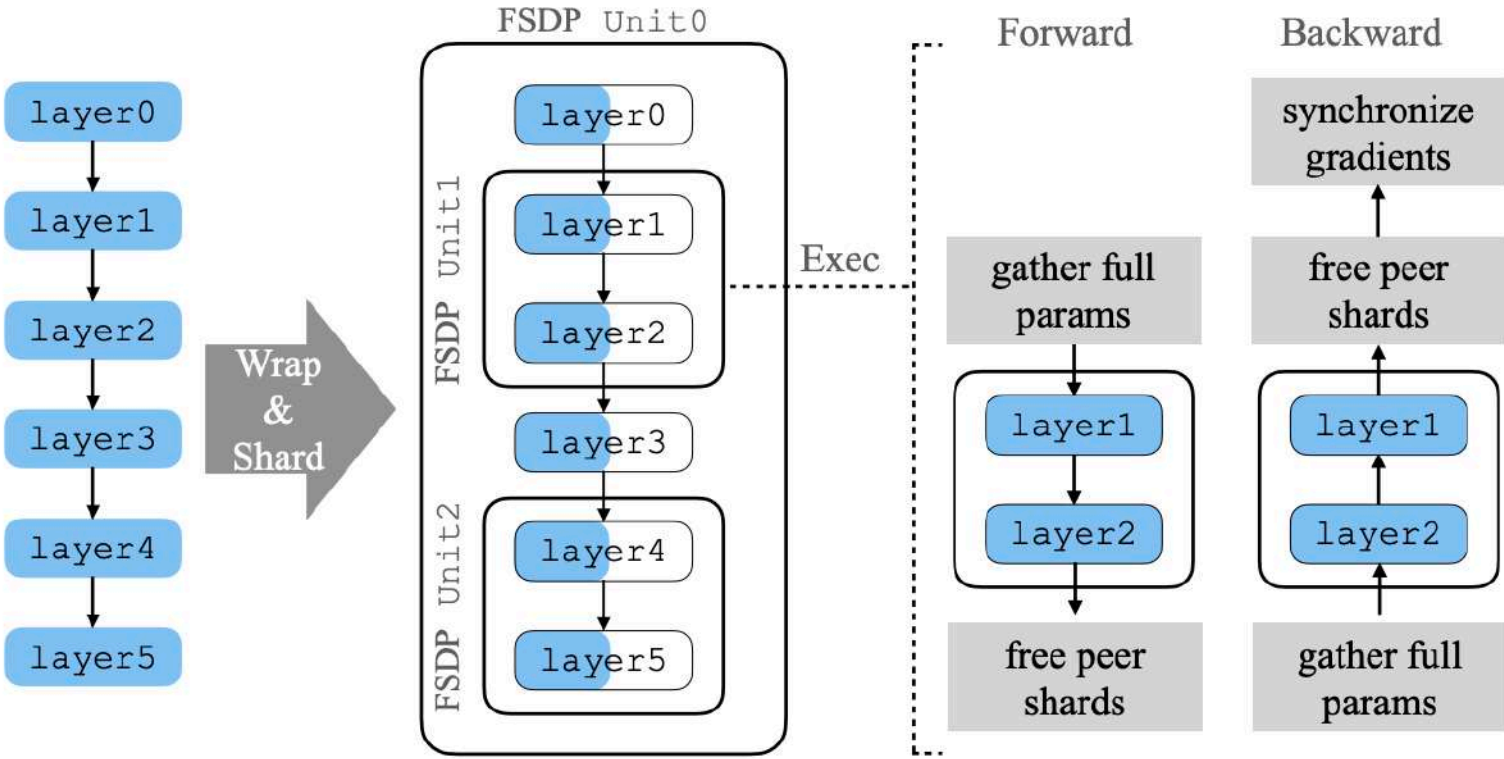

Load shard
From CPU if
CPU Offloaded
LOAD-
MODEL
SHARD
ALL-
GATHER
FORWARD
(LOCAL)
FREE FULL
WEIGHTS
FSDP instance 1: N layers
Offload grads to
CPU if CPU
offload is enabled
ALL-
GATHER
BACKWARD
(LOCAL)
REDUCE-
SCATTER
FREE FULL
WEIGHTS
FSDP instance 1: N layers
FSDP instance N: M layers
UPDATE
WEIGHTS
(LOCAL)
GATHER
WEIGHTS
(ALL_GATHER)
GATHER
WEIGHTS
(ALL_GATHER)
SYNC GRADS
(REDUCE_SCATTER)
Data
LOAD-
MODEL
SHARD
ALL-
GATHER
FORWARD
(LOCAL)
FREE FULL
WEIGHTS
FSDP instance 1: N layers
ALL-
GATHER
BACKWARD
(LOCAL)
REDUCE-
SCATTER
FREE FULL
WEIGHTS
FSDP instance 1: N layers
FSDP instance N: M layers
UPDATE
WEIGHTS
(LOCAL)
Load shard
From CPU if
CPU Offloaded
Offload grads to
CPU if CPU
offload is enabled

FSDP2

```python
from torch.distributed.fsdp import fully_shard

mesh_2d = init_device_mesh(
    "cuda",
    mesh_shape=(2, 8),
    mesh_dim_names=("dp", "tp"),
)
model = Model()

for layer in model.layers:
    fully_shard(
        module, # (module1, module2)
        mesh=dp_mesh,
        reshard_after_forward=True, # ZeRO-3
        mp_policy=MixedPrecisionPolicy(
            param_dtype=torch.float16,
            reduce_dtype=torch.float32,
        ),
        offload_policy=CPUOffloadPolicy(),
    )

fully_shard(model, ...)
```

```python
for step in ...:
    for gas_step in ...:
        is_last_backward = gas_step == num_gas_steps - 1
        # ZeRO-3
        model.set_reshard_after_backward(is_last_backward)
        # ZeRO-2
        model.requires_gradient_sync(is_last_backward)

    loss = loss_fn(model(inputs), targets)
    ...
```

FSDP2


layer0
layer1
layer2
layer3
layer4
layer5
Wrap & Shard
FSDP Unit0
FSDP Unit1
FSDP Unit2
layer0
layer1
layer2
layer3
layer4
layer5
Exec
Forward
Backward
gather full params
free peer shards
synchronize gradients
free peer shards
gather full params

FSDP2 — hooks

register_forward_pre_hook(*hook*, ***, *prepend=False*, *with_kwargs=False*) [SOURCE]

Register a forward pre-hook on the module.

The hook will be called every time before `forward()` is invoked.

register_forward_hook(*hook*, ***, *prepend=False*, *with_kwargs=False*, *always_call=False*) [SOURCE]

Register a forward hook on the module.

The hook will be called every time after `forward()` has computed an output.

FSDP2 — pre-forward

```
def pre_forward(module, args):
    module.unshard() # in all-gather stream
    module.wait_for_unshard() # sync compute (default) stream with all-gather stream
    module._register_post_backward_hook(args)
    return args

def unshard(module):
    with torch.cuda.stream(all_gather_stream):
        module.all_gather()
    module.all_gather_event = all_gather_stream.record_event()
    module.set_unsharded_params()

def wait_for_unshard(module):
    torch.cuda.default_stream().wait_event(module.all_gather_event)

def fully_shard(module, ... ):
    ...
    module.register_forward_pre_hook(pre_forward)
```

FSDP2 — post-forward

```
def post_forward(module, args, output):
    module.reshard()
    module._record_post_forward()
    module._register_pre_backward_hook(output)
    return output

def reshard(module):
    module.set_sharded_params() # and free unsharded params

def _record_post_forward(module):
    post_forward_index = len(module.comm_ctx.post_forward_order)
    module.comm_ctx.post_forward_order.append(module)
    module._post_forward_indices.append(post_forward_index)

def fully_shard(module, ... ):
    ...
    module.register_forward_hook(post_forward)
```

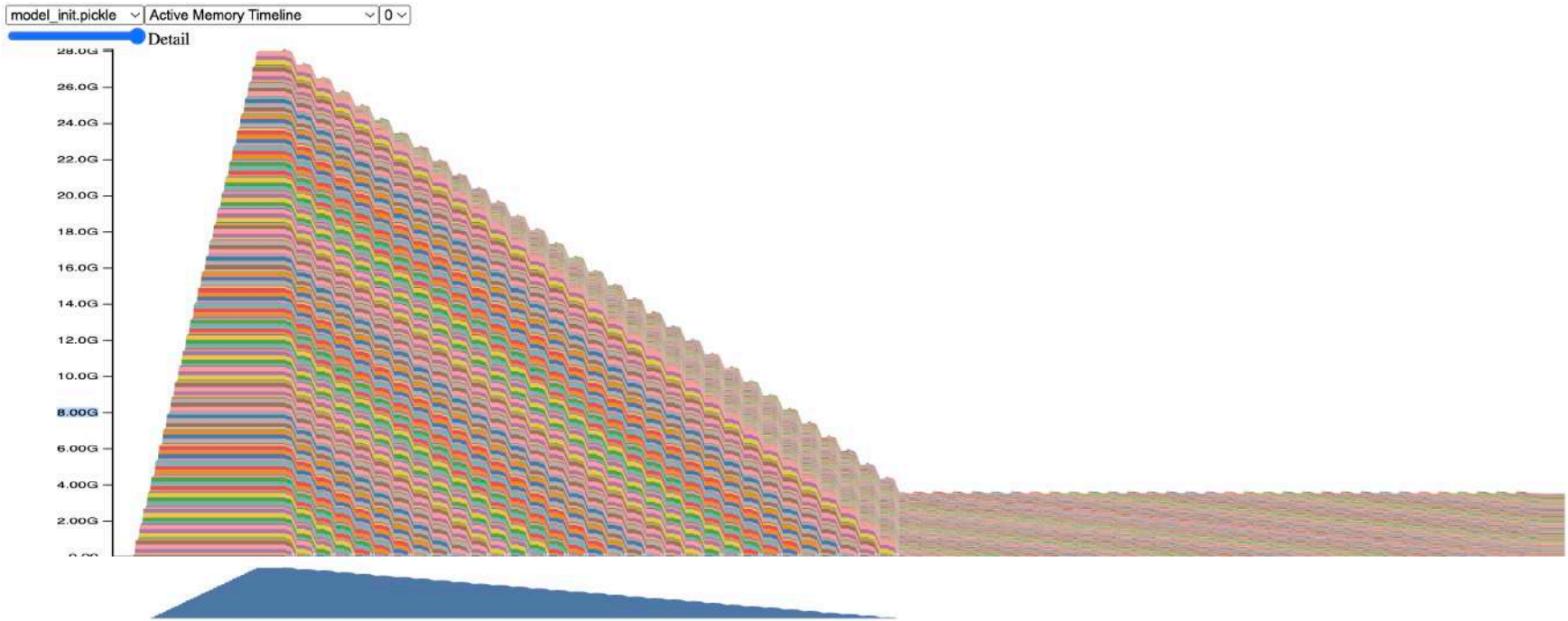
FSDP2 — pre-backward

```
def pre_backward(module, *unused):
    module.unshard()  # no-op if prefetched
    module.wait_for_unshard()
    module._backward_prefetch()

def _backward_prefetch(module):
    curr_index = module._post_forward_indices.pop()
    target_index = curr_index - 1
    target_module = self.comm_ctx.post_forward_order[target_index]
    target_module.unshard()

def _register_pre_backward_hook(self, output):
    for t in output:
        if torch.is_tensor(t) and t.requires_grad:
            t.register_hook(self._pre_backward)
    return output
```

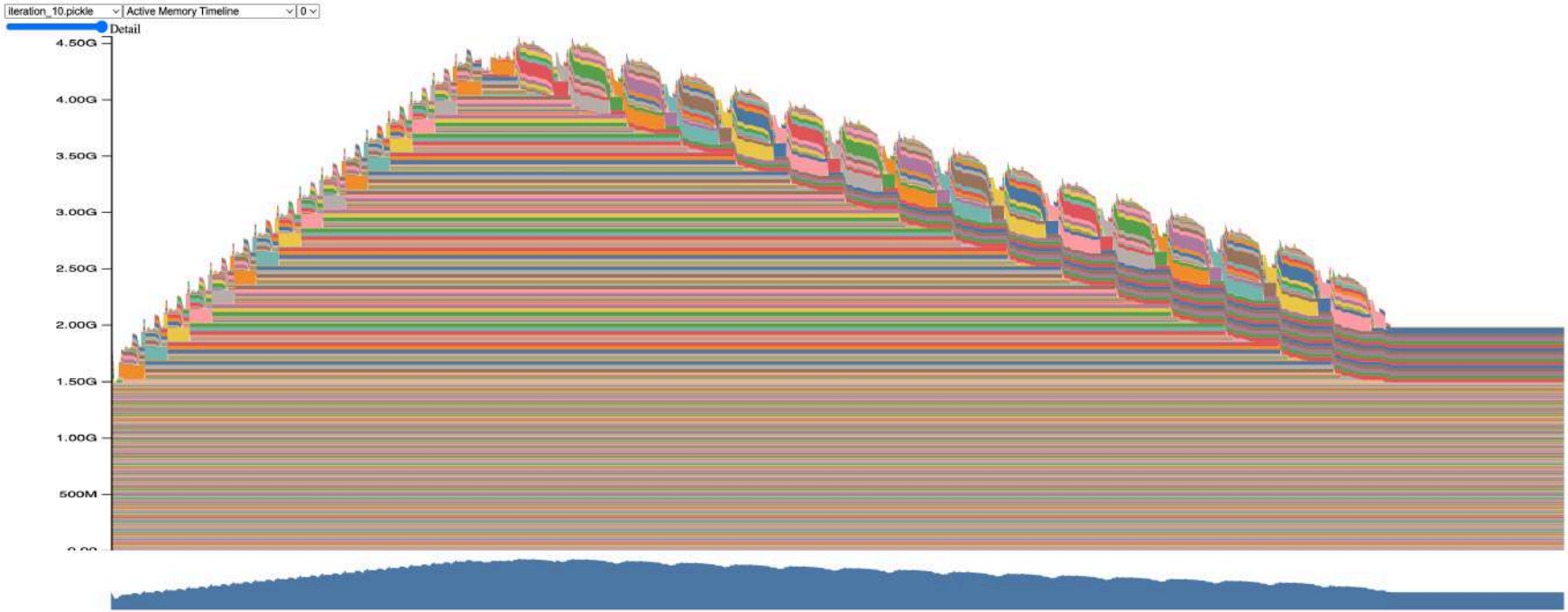
FSDP2 — post-backward

```
def post_backward(module, *unused: Any):
    if module.reshard_after_backward:
        module.reshard()
    if module.reduce_grads:
        reduce_scatter_stream.wait_stream(torch.cuda.default_stream())
        with torch.cuda.stream(reduce_scatter_stream):
            module.reduce_scatter_grads()
        reduce_event = reduce_scatter_stream.record_event()

def _register_post_backward_hook(module, args):
    RegisterPostBackwardFunction.apply(self, *args)

class RegisterPostBackwardFunction(torch.autograd.Function):
    @staticmethod
    def forward(ctx, module, *inputs):
        ctx.module = module
        return inputs

    @staticmethod
    def backward(ctx, *grads):
        module.post_backward()
        return (None,) + grads
```

FSDP2 — memory



FSDP2 — memory

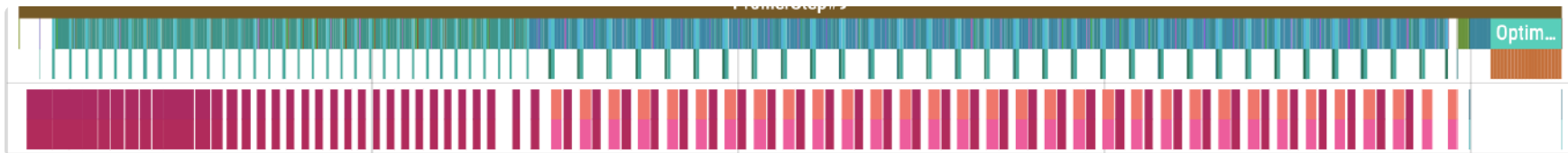


Computation / communication overlap

- Implicit prefetching
  - в `pre_forward`
- Explicit prefetching
  - в `pre_backward`
  - можно задать руками

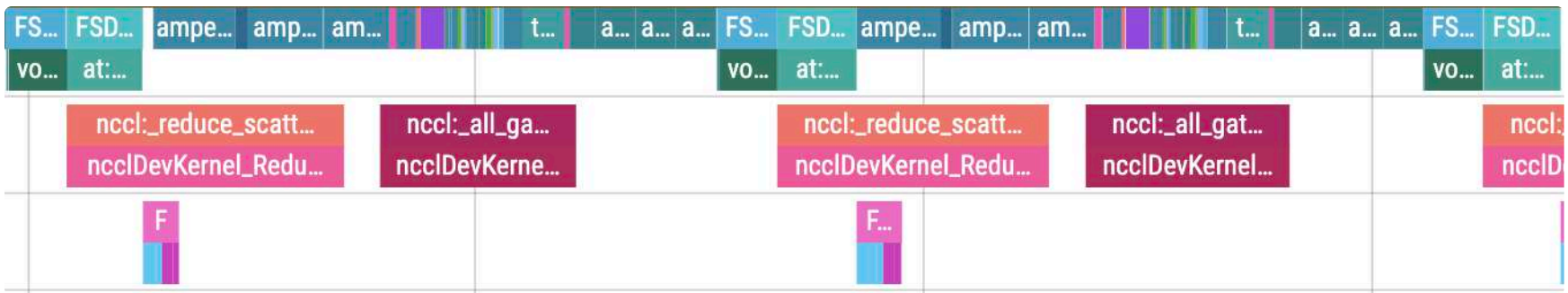
```
module.set_modules_to_forward_prefetch(modules)
module.set_modules_to_backward_prefetch(modules)
```

Подробнее про работу со стримами

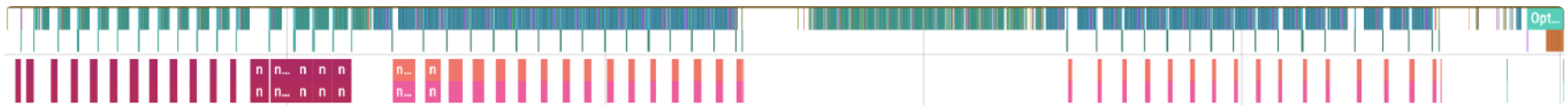


Подробнее про работу со стримами — forward

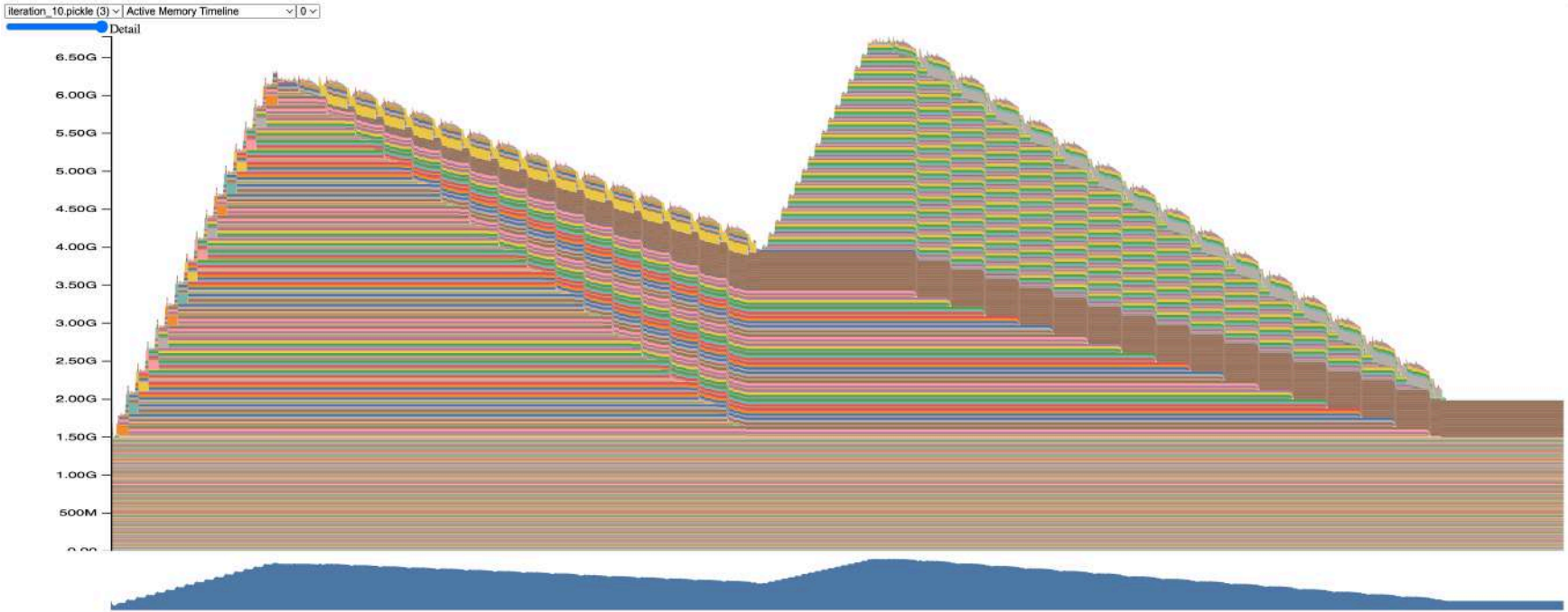
Подробнее про работу со стримами — backward



ZeRO-2

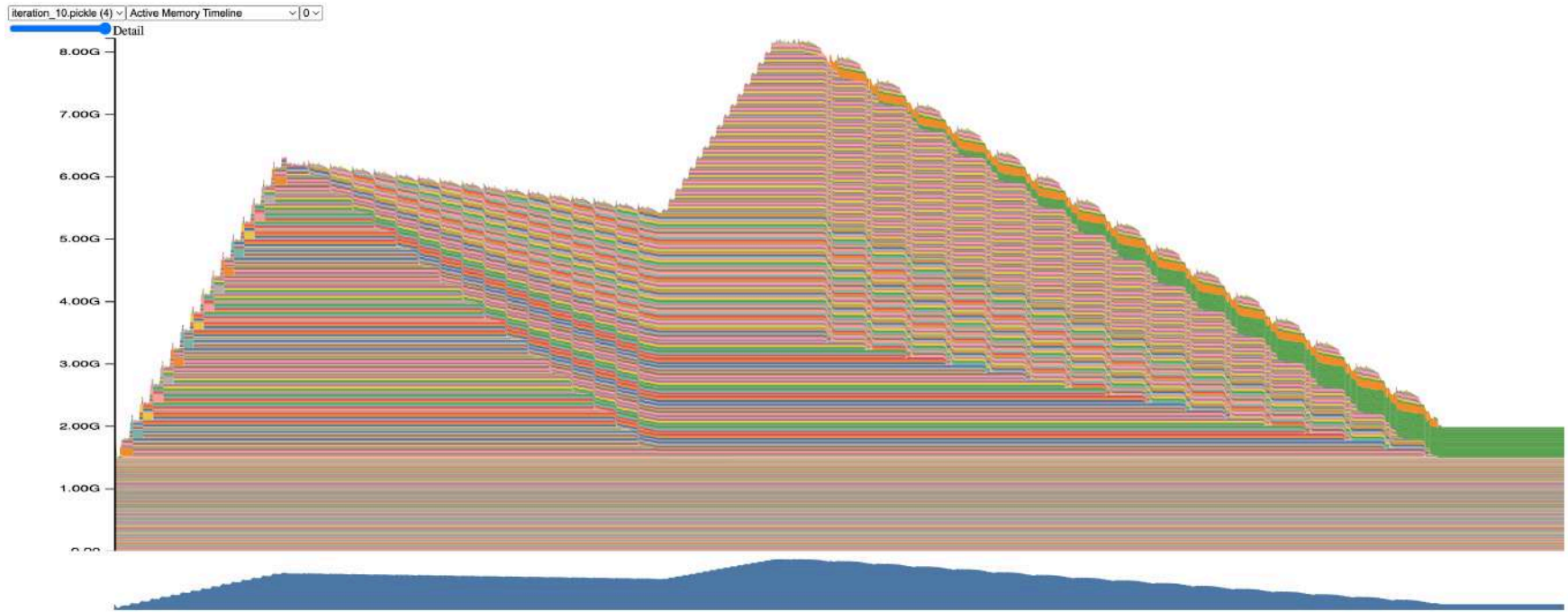


ZeRO-2


iteration_10.pickle (3)
Active Memory Timeline
0
Detail
6.50G
6.00G
5.50G
5.00G
4.50G
4.00G
3.50G
3.00G
2.50G
2.00G
1.50G
1.00G
500M

ZeRO-1

ZeRO-1


iteration_10.pickle (4)
Active Memory Timeline
0
Detail
8.00G
7.00G
6.00G
5.00G
4.00G
3.00G
2.00G
1.00G

HSDP

```
mesh_2d = init_device_mesh(
    "cpu",
    mesh_shape=(2, 8),
    mesh_dim_names=("dp_replicate", "dp_shard"),
)

fully_shard(
    module,
    mesh=mesh_2d,
    ...
)
```

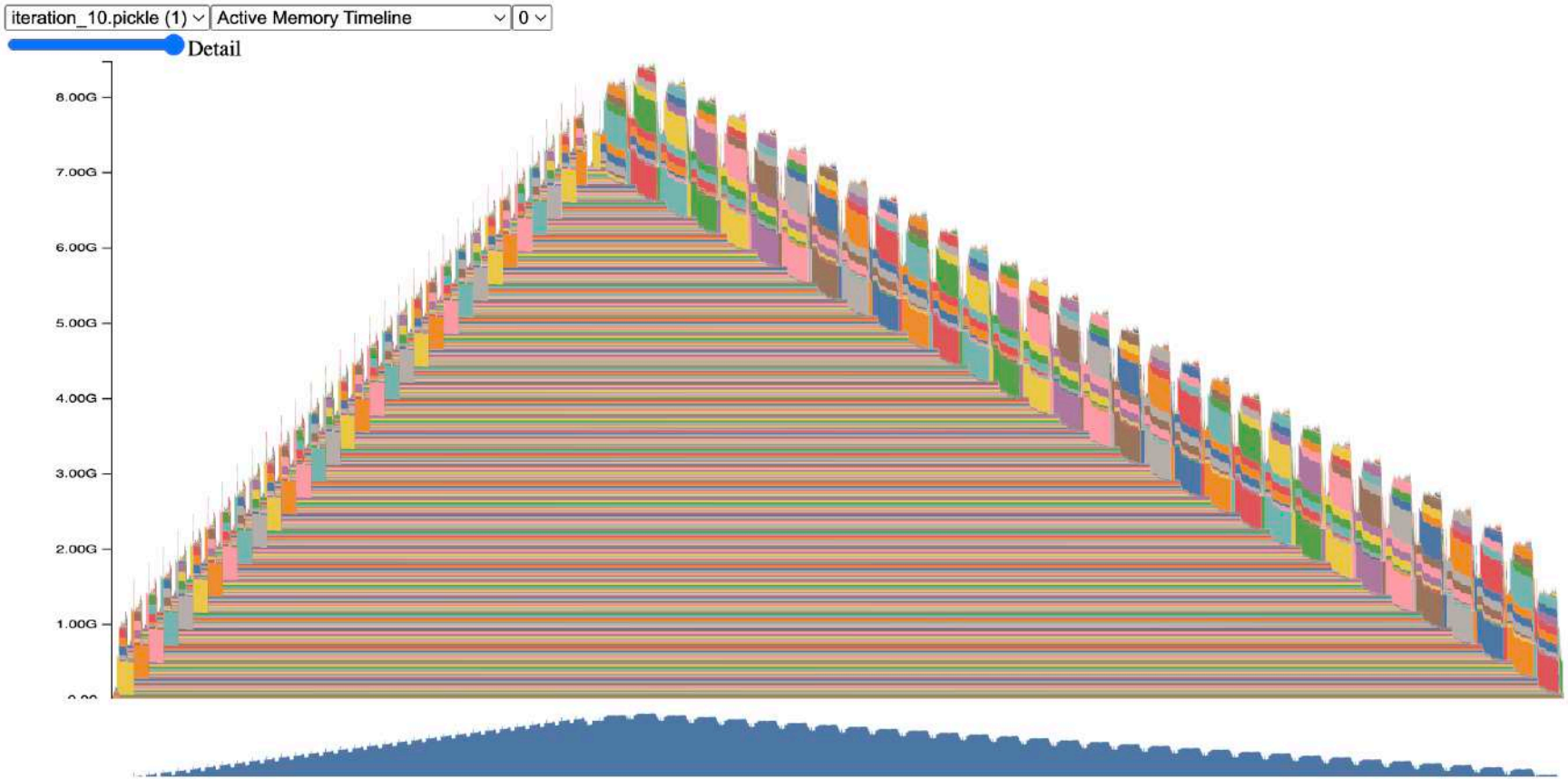
- логика становится заметно сложнее, показывать не буду(

CPU offloading

- ZeRO-Offload

```
with torch.device("cpu"):
    model = Model()

fully_shard(
    module,
    ...
    offload_policy=CPUOffloadPolicy(),
)

def unshard(module):
    sharded_param = sharded_param.to(
        device,
        non_blocking=True,
    )
    ...
    module.all_gather()

def post_backward(module):
    new_sharded_grad = new_sharded_grad.to(
        torch.device("cpu"),
        non_blocking=True
    )
```

CPU offloading

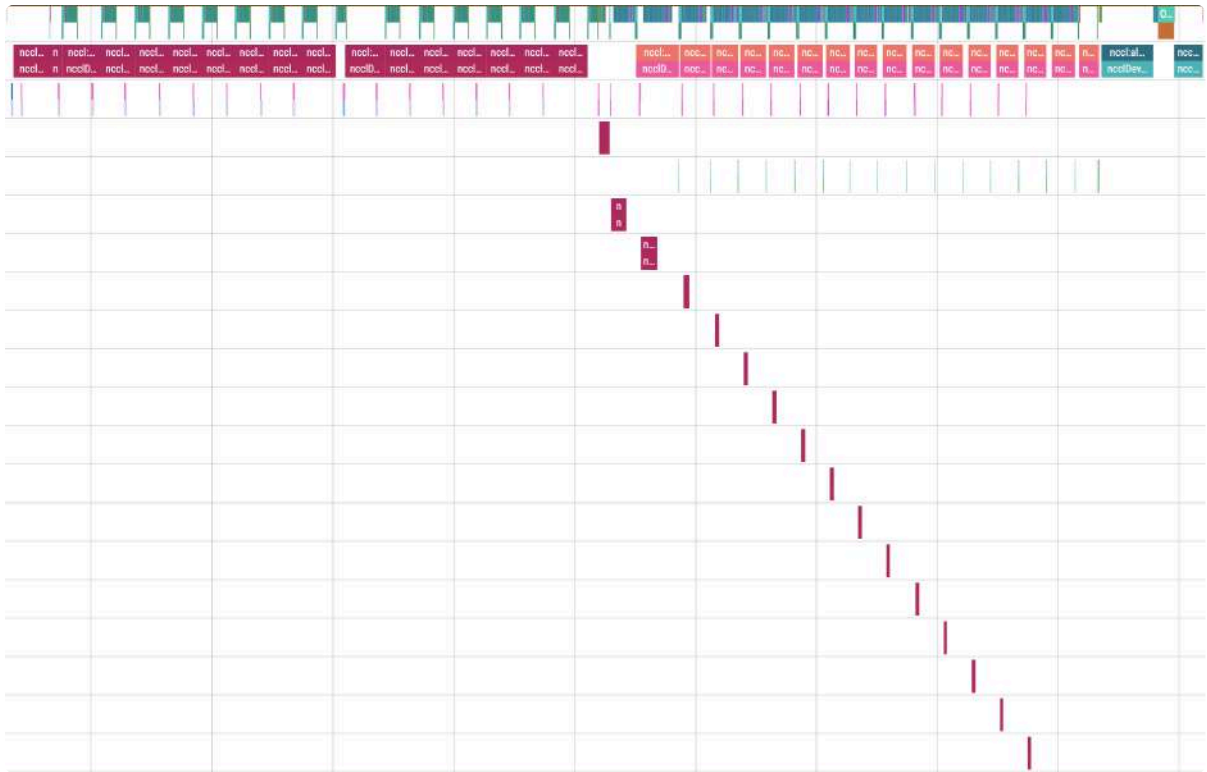


hpZ

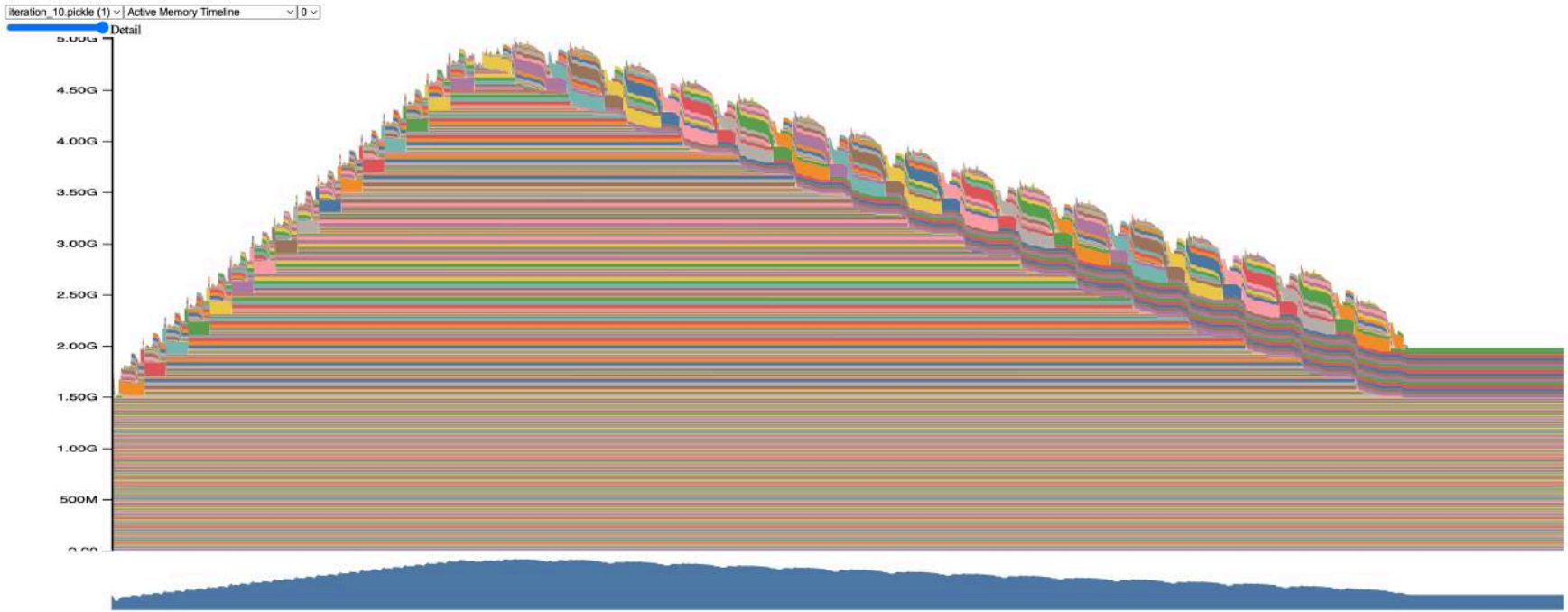
- ZeRO++

```
mesh = init_device_mesh(
    "cuda",
    mesh_shape=(16,),
    mesh_dim_names=("dp",),
)
fully_shard(
    module,
    mesh,
    ...
    reshard_after_forward=8,
)
```

hpZ



hpZ


iteration_10.pickle (1)
Active Memory Timeline
0
Detail
4.50G
4.00G
3.50G
3.00G
2.50G
2.00G
1.50G
1.00G
500M

PyTorch DCP

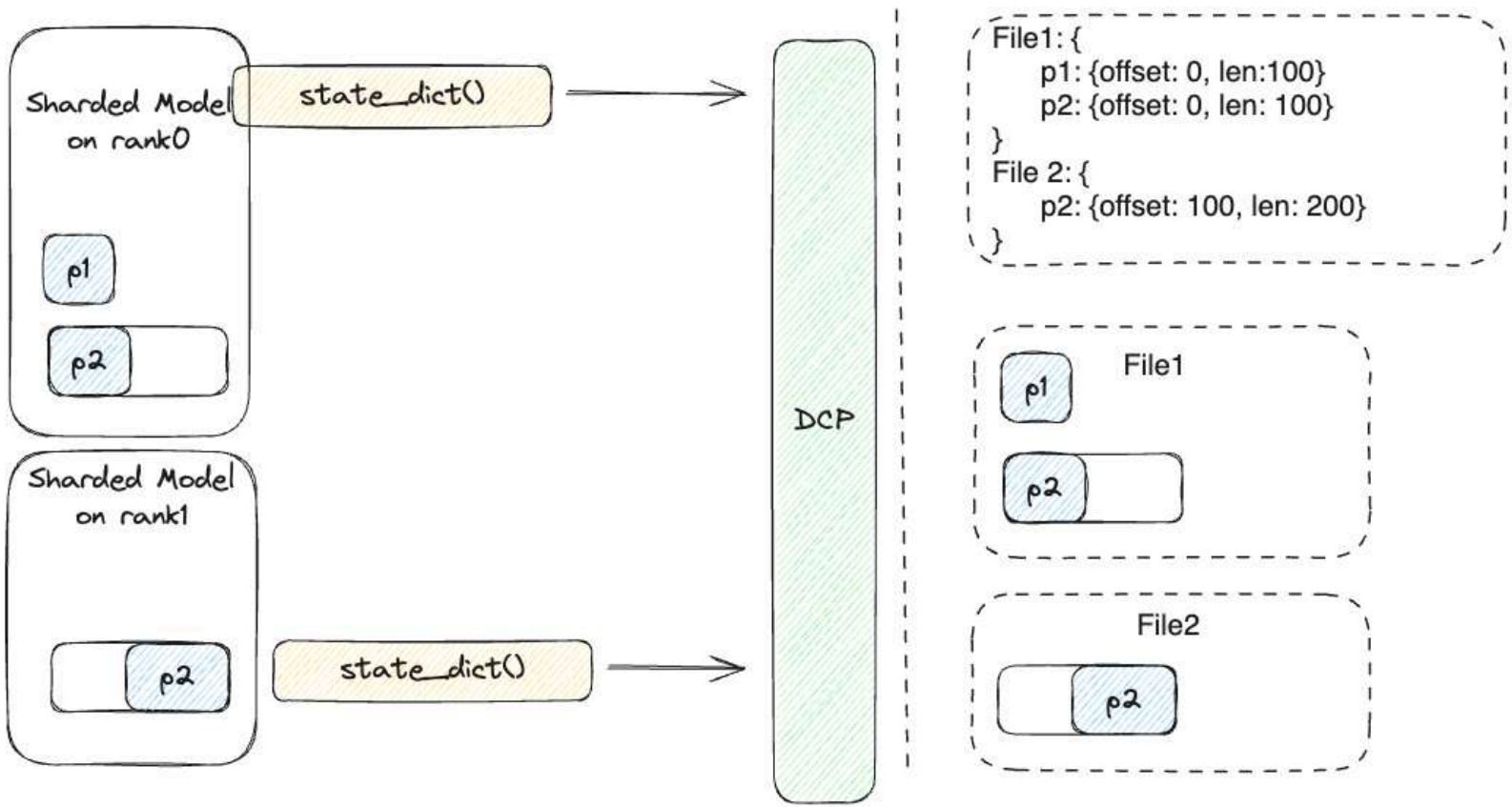
- два вида `state_dict`
  - `SHARDED_STATE_DICT`
  - `FULL_STATE_DICT`
- в FSDP2 всегда sharded, но состоит из DTensor-ов
  - с помощью `.redistribute()` можно менять шардирование чекпоинта
- DCP умеет эффективно отгружать чекпоинты с минимальным оверхедом

PyTorch DCP

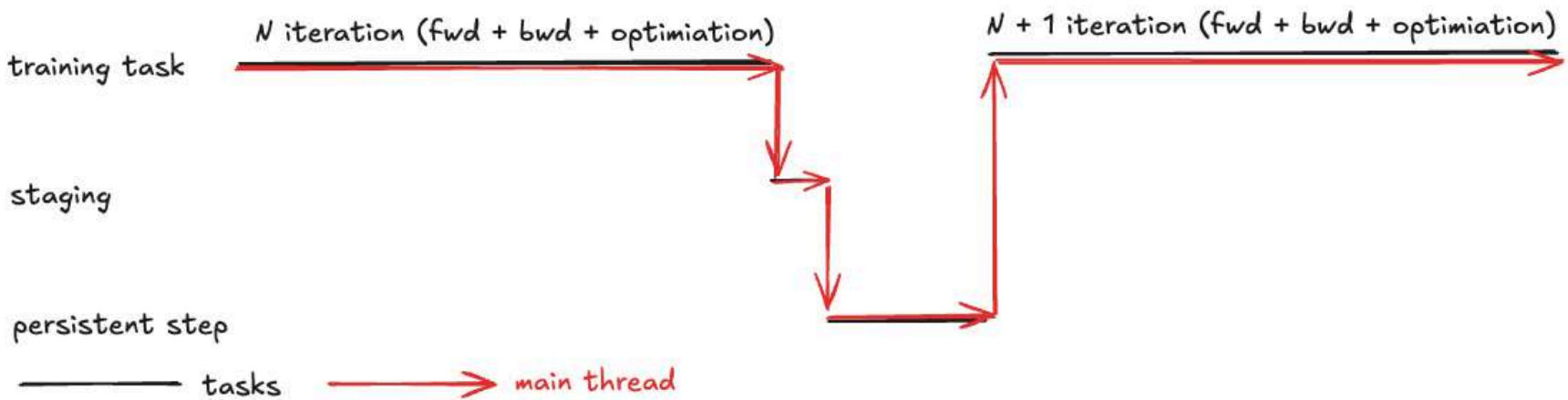
```
import torch.distributed.checkpoint as dcp
model = Model()
fully_shard(model)
optimizer = Optimizer(model.parameters())

state_dict = {
    "model": model.state_dict(),
    "optimizer": optimizer.state_dict()
}
dcp.state_dict_saver.save(state_dict)
dcp.state_dict_loader.load(state_dict)
```

- truthfully i's a bit more complicated

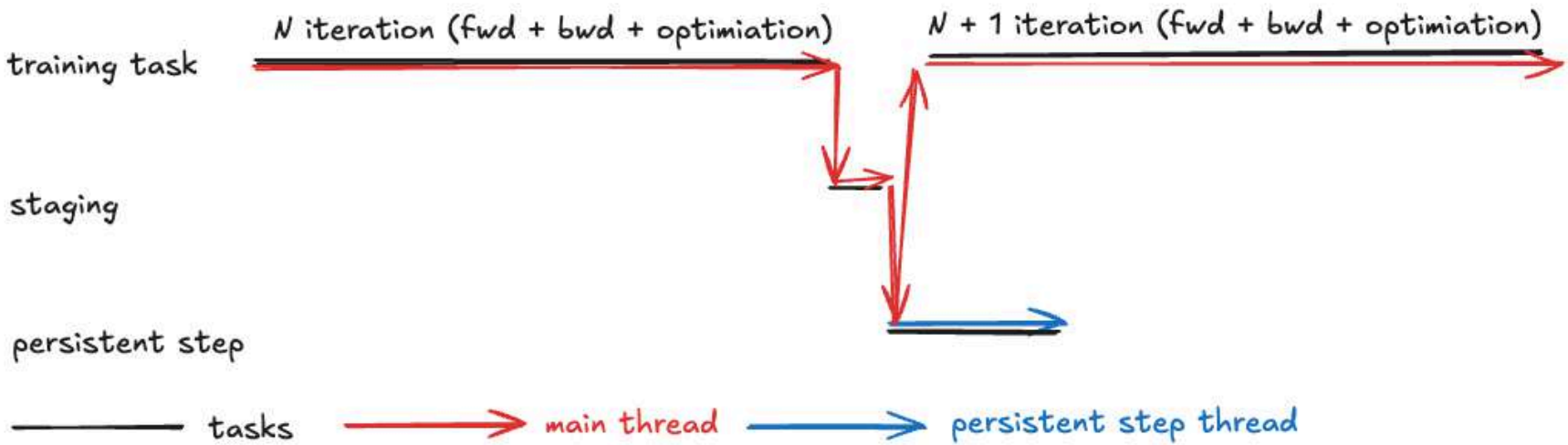
PyTorch DCP


Sharded Model
on rank0
state_dict()
p1
p2
Sharded Model
on rank1
p2
state_dict()
DCP
File1: {
p1: {offset: 0, len:100}
p2: {offset: 0, len: 100}
}
File 2: {
p2: {offset: 100, len: 200}
}
File1
p1
p2
File2
p2

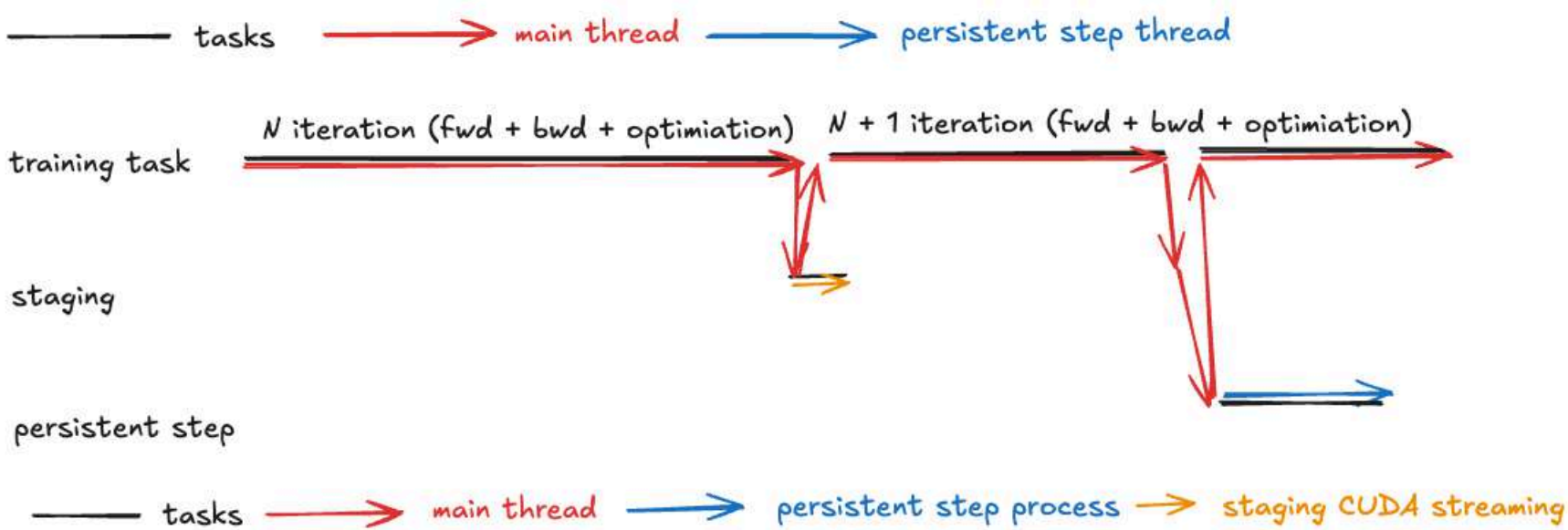
PyTorch DCP


N iteration (fwd + bwd + optimiation)
N + 1 iteration (fwd + bwd + optimiation)
training task
staging
persistent step
tasks
main thread

PyTorch DCP


N iteration (fwd + bwd + optimiation)
N + 1 iteration (fwd + bwd + optimiation)
training task
staging
persistent step
tasks
main thread
persistent step thread

PyTorch DCP


tasks
main thread
persistent step thread
training task
N iteration (fwd + bwd + optimiation)
N + 1 iteration (fwd + bwd + optimiation)
staging
persistent step
tasks
main thread
persistent step process
staging CUDA streaming

Garbage collection tuning

```
gc.disable()
gc.collect(1)

... init

for step in ...:
    if step > 1 and step % _gc_freq == 0:
        gc.collect(1)

    ... step
```

Extras

- SimpleFSDP
- `unshard_in_backward`
- meta device init
- compile

Code

- можно поиграться со всем этим в ноутбуке
- пайплайн отладки