Eager execution

CS 20: TensorFlow for Deep Learning Research
Lecture 4
1/24/2017

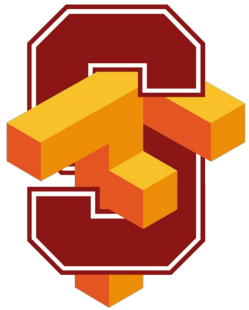
- **Assignment 1 is out! (due 1/31)**
- **Gitter chatroom**

Agenda

Eager execution

Linear regression in eager

Interactive Coding!



Eager Execution

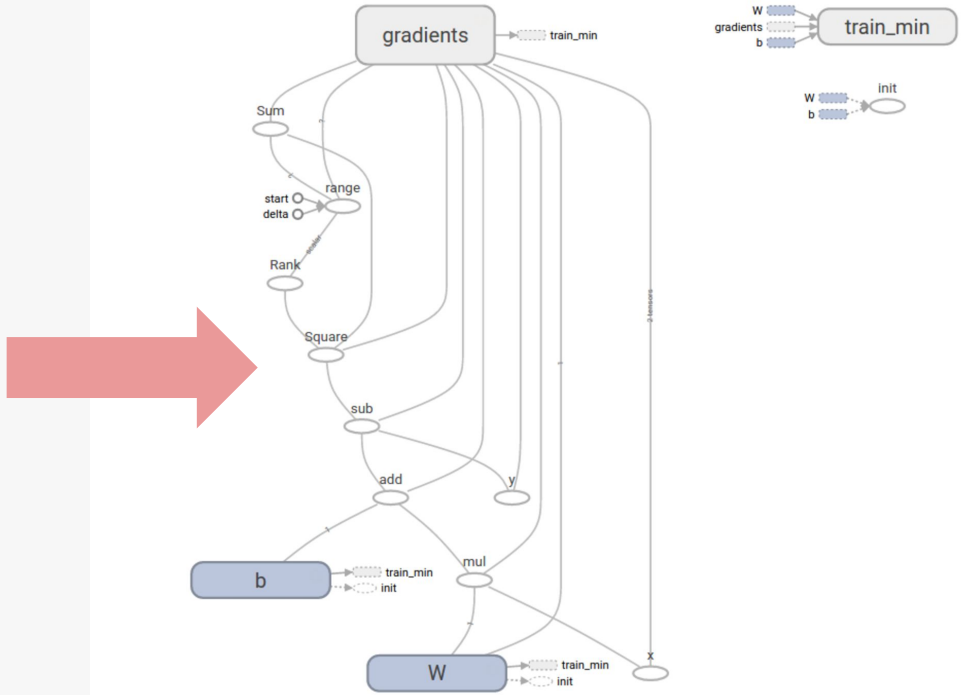
Presented by Akshay Agrawal
akshayka@{cs.stanford.edu, google.com}

TensorFlow Today: Declarative (Graphs)

```python
import numpy as np
import tensorflow as tf

# Model parameters
W = tf.Variable([.3], tf.float32)
b = tf.Variable([-.3], tf.float32)
# Model input and output
x = tf.placeholder(tf.float32)
linear_model = W * x + b
y = tf.placeholder(tf.float32)
# loss
loss = tf.reduce_sum(tf.square(linear_model - y)) # sum of the squares
# optimizer
optimizer = tf.train.GradientDescentOptimizer(0.01)
train = optimizer.minimize(loss)
# training data
x_train = [1,2,3,4]
y_train = [0,-1,-2,-3]
# training loop
init = tf.global_variables_initializer()
sess = tf.Session()
sess.run(init) # reset values to wrong
for i in range(1000):
  sess.run(train, {x:x_train, y:y_train})

# evaluate training accuracy
curr_W, curr_b, curr_loss  = sess.run([W, b, loss], {x:x_train, y:y_train})
print("W: %s b: %s loss: %s"%(curr_W, curr_b, curr_loss))
```



Graphs are ...

Optimizable

- automatic buffer reuse
- constant folding
- inter-op parallelism
- automatic trade-off between compute and memory

Deployable

- the Graph is an intermediate representation for models

Rewritable

- experiment with automatic device placement or quantization

But graphs are also ...

Difficult to debug

- errors are reported long after graph construction
- execution cannot be debugged with `pdb` or print statements

Un-Pythonic

- writing a TensorFlow program is an exercise in metaprogramming
- control flow (e.g., `tf.while_loop`) differs from Python
- can't easily mix graph construction with custom data structures

```
Traceback (most recent call last):
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 1350, in _do_call
    return fn(*args)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 1329, in _run_fn
    status, run_metadata)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/framework/errors_impl.py", line 473, in __exit__
    c_api.TF_GetCode(self.status.status))
tensorflow.python.framework.errors_impl.InvalidArgumentError: indices[0] = 3081 is not in [0, 128)
         [[Node: loss/nce_loss/embedding_lookup_1 = Gather[Tindices=DT_INT64, Tparams=DT_FLOAT, _class=["loc:@nce_bias"], validate_indices=true, _device="/job:localhost/replica:0/task:0/device:CPU:0"](nce_bias/read, loss/nce_loss/concat)]]

During handling of the above exception, another exception occurred:

Traceback (most recent call last):
  File "04_word2vec.py", line 102, in <module>
    main()
  File "04_word2vec.py", line 99, in main
    word2vec(dataset)
  File "04_word2vec.py", line 82, in word2vec
    loss_batch, _ = sess.run([loss, optimizer])
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 895, in run
    run_metadata_ptr)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 1128, in _run
    feed_dict_tensor, options, run_metadata)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 1344, in _do_run
    options, run_metadata)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/client/session.py", line 1363, in _do_call
    raise type(e)(node_def, op, message)
tensorflow.python.framework.errors_impl.InvalidArgumentError: indices[0] = 3081 is not in [0, 128)
         [[Node: loss/nce_loss/embedding_lookup_1 = Gather[Tindices=DT_INT64, Tparams=DT_FLOAT, _class=["loc:@nce_bias"], validate_indices=true, _device="/job:localhost/replica:0/task:0/device:CPU:0"](nce_bias/read, loss/nce_loss/concat)]]

Caused by op 'loss/nce_loss/embedding_lookup_1', defined at:
  File "04_word2vec.py", line 102, in <module>
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  File "04_word2vec.py", line 99, in main
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  File "04_word2vec.py", line 65, in word2vec
    num_classes=VOCAB_SIZE), name='loss')
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/nn_impl.py", line 1212, in nce_loss
    name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/nn_impl.py", line 1046, in _compute_sampled_logits
    biases, all_ids, partition_strategy=partition_strategy)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/embedding_ops.py", line 325, in embedding_lookup
    transform_fn=None)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/embedding_ops.py", line 150, in _embedding_lookup_and_transform
    result = _clip(_gather(params[0], ids, name=name), ids, max_norm)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/embedding_ops.py", line 54, in _gather
    return array_ops.gather(params, ids, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/array_ops.py", line 2585, in gather
    params, indices, validate_indices=validate_indices, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/gen_array_ops.py", line 1864, in gather
    validate_indices=validate_indices, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/framework/op_def_library.py", line 787, in _apply_op_helper
    op_def=op_def)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/framework/ops.py", line 3160, in create_op
    op_def=op_def)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/framework/ops.py", line 1625, in __init__
    self._traceback = self._graph._extract_stack()  # pylint: disable=protected-access

InvalidArgumentError (see above for traceback): indices[0] = 3081 is not in [0, 128)
         [[Node: loss/nce_loss/embedding_lookup_1 = Gather[Tindices=DT_INT64, Tparams=DT_FLOAT, _class=["loc:@nce_bias"], validate_indices=true, _device="/job:localhost/replica:0/task:0/device:CPU:0"](nce_bias/read, loss/nce_loss/concat)]]
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    c_api.TF_GetCode(self.status.status))
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         [[Node: loss/nce_loss/embedding_l                                                                                                as/read, loss/nce_loss/concat)]]

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    loss_batch, _ = sess.run([loss, optimi
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         [[Node: loss/nce_loss/embedding_l                                                                                                as/read, loss/nce_loss/concat)]]

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  File "04_word2vec.py", line 99, in main
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    num_classes=VOCAB_SIZE), name='loss')
  File "/Users/Akshay/pyenvs/tf-1.50rc1/li
    name=name)
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    biases, all_ids, partition_strategy=pa
  File "/Users/Akshay/pyenvs/tf-1.50rc1/li
    transform_fn=None)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/li
    result = _clip(_gather(params[0], ids,
  File "/Users/Akshay/pyenvs/tf-1.50rc1/li
    return array_ops.gather(params, ids, n
  File "/Users/Akshay/pyenvs/tf-1.50rc1/li
    params, indices, validate_indices=vali
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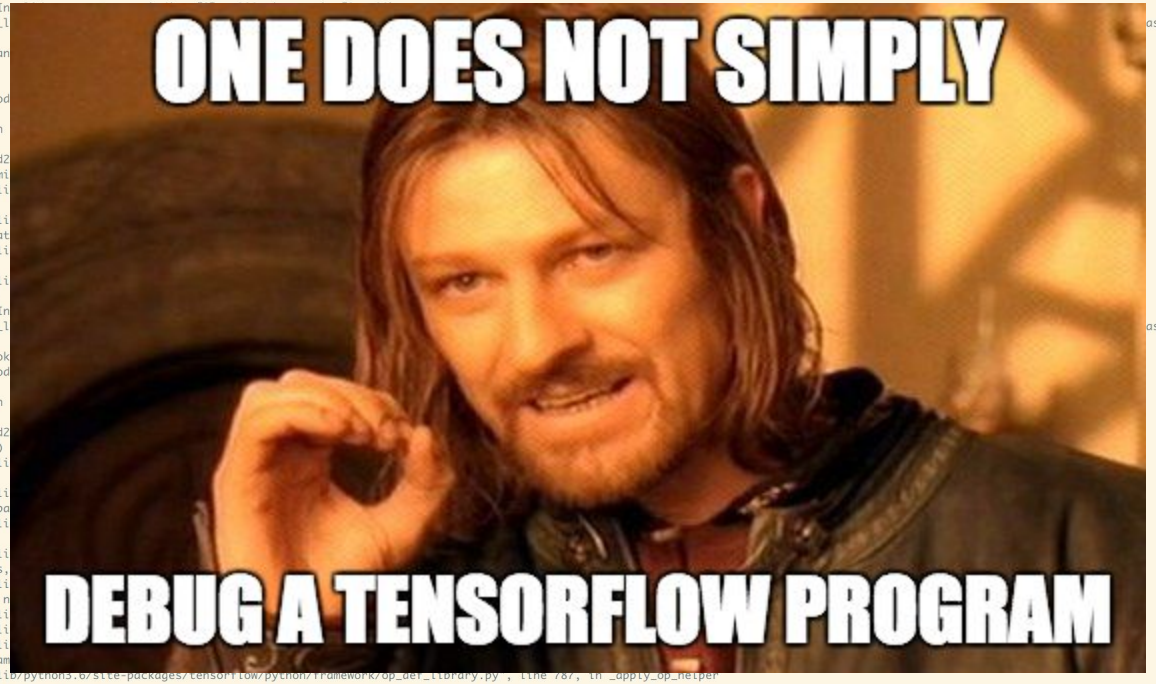

What if...

You could execute TensorFlow operations imperatively,
directly from Python?

Eager Execution

"A NumPy-like library for numerical computation with support for GPU acceleration and automatic differentiation, and a flexible platform for machine learning research and experimentation."

- the eager execution user guide

Live Demo

```
$python
import tensorflow # version >= 1.50
import tensorflow.contrib.eager as tfe
tfe.enable_eager_execution()
```

Key Advantages

- Compatible with Python debugging tools
  - `pdb.set_trace()` to your heart's content!
- Provides immediate error reporting
- Permits use of Python data structures
  - e.g., for structured input
- Enables easy, Pythonic control flow
  - `if` statements, `for` loops, recursion, oh my!

```
i = tf.constant(0)
while i < 1000:
  i = tf.add(i, 1)
  print("I could do this all day! %d" % i)
```

```
Traceback (most recent call last):
  File "04_word2vec_eager.py", line 83, in <module>
    main()
  File "04_word2vec_eager.py", line 72, in main
    loss_batch, grads = val_and_grad_fn(center_words, target_words)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/eager/backprop.py", line 349, in grad_fn
    end_node = f(*args)
  File "04_word2vec_eager.py", line 51, in word2vec
    num_classes=VOCAB_SIZE))
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/nn_impl.py", line 1212, in nce_loss
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  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/embedding_ops.py", line 52, in _gather
    return params.sparse_read(ids, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/resource_variable_ops.py", line 692, in sparse_read
    self._handle, indices, dtype=self._dtype, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/ops/gen_resource_variable_ops.py", line 250, in resource_gather
    attrs=_attrs, ctx=_ctx, name=name)
  File "/Users/Akshay/pyenvs/tf-1.50rc1/lib/python3.6/site-packages/tensorflow/python/eager/execute.py", line 66, in quick_execute
    six.raise_from(core._status_to_exception(e.code, message), None)
  File "<string>", line 3, in raise_from
tensorflow.python.framework.errors_impl.InvalidArgumentError: indices[0] = 3081 is not in [0, 128) [Op:ResourceGather] name: nce_loss/embedding_lookup/
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    num_classes=VOCAB_SIZE))
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    attrs=_attrs, ctx=_ctx, name=name)
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    six.raise_from(core._status_to_exc
  File "<string>", line 3, in raise_fr
tensorflow.python.framework.errors_imp
```

Eager execution simplifies your code

You no longer need to worry about ...

1. placeholders
2. sessions
3. control dependencies
4. "lazy loading"
5. {name, variable, op} scopes

Boilerplate

```
x = tf.placeholder(tf.float32, shape=[1, 1])
m = tf.matmul(x, x)

print(m)
# Tensor("MatMul:0", shape=(1, 1), dtype=float32)

with tf.Session() as sess:
  m_out = sess.run(m, feed_dict={x: [[2.]]})
print(m_out)
# [[4.]]
```

Code like this...

~~Boilerplate~~

```
x = [[2.]]  # No need for placeholders!
m = tf.matmul(x, x)

print(m)  # No sessions!
# tf.Tensor([[4.]], shape=(1, 1), dtype=float32)
```

Becomes this

"Lazy Loading"

```
x = tf.random_uniform([2, 2])

with tf.Session() as sess:
  for i in range(x.shape[0]):
    for j in range(x.shape[1]):
      print(sess.run(x[i, j]))
```

Each iteration adds nodes to the graph

~~"Lazy Loading"~~

```
x = tf.random_uniform([2, 2])

for i in range(x.shape[0]):
  for j in range(x.shape[1]):
    print(x[i, j])
```

Tensors Act Like NumPy Arrays

```
x = tf.constant([1.0, 2.0, 3.0])

# Tensors are backed by NumPy arrays
assert type(x.numpy()) == np.ndarray
squared = np.square(x) # Tensors are compatible with NumPy functions

# Tensors are iterable!
for i in x:
  print(i)
```

Caveat: use tf.equal to compare Tensors, not ==

Gradients

Gradients

Automatic differentiation is built into eager execution

Under the hood ...

- Operations are recorded on a **tape**
- The tape is **played back** to compute gradients
  - This is reverse-mode differentiation (backpropagation).

Gradients

```
def square(x):
  return x ** 2

grad = tfe.gradients_function(square)

print(square(3.))    # tf.Tensor(9., shape=(), dtype=float32)
print(grad(3.))      # [tf.Tensor(6., shape=(), dtype=float32))]
```

Differentiate w.r.t. input of square

Gradients

Use **`tfe.Variable`** when eager execution is enabled.

```
x = tfe.Variable(2.0)
def loss(y):
  return (y - x ** 2) ** 2

grad = tfe.implicit_gradients(loss)

print(loss(7.))  # tf.Tensor(9., shape=(), dtype=float32)
print(grad(7.))  # [(<tf.Tensor: -24.0, shape=(), dtype=float32>,
                   <tf.Variable 'Variable:0' shape=()
                    dtype=float32, numpy=2.0>)]
```

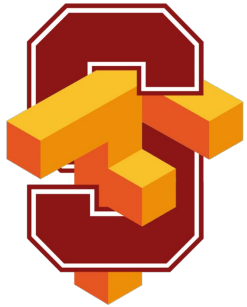
Differentiate w.r.t. variables used to compute `loss`

Gradients

APIs for computing gradients work even when eager execution is not enabled

- `tfe.gradients_function()`
- `tfe.value_and_gradients_function()`
- `tfe.implicit_gradients()`
- `tfe.implicit_value_and_gradients()`

See the user guide for documentation



Huber Regression with Eager Execution

Interactive Coding

`04_regression_eager_starter.py`

It's not *that* different

A Collection of Operations

TensorFlow = Operation Kernels + Execution

- Graph construction: Execute compositions of operations with Sessions
- Eager execution: Execute compositions with Python

A Collection of Operations

Majority of TF API works regardless of whether eager execution is enabled.

- But, when eager execution is enabled ...
  - prefer **`tfe.`**`Variable` under eager execution (compatible with graph construction)
  - manage your own variable storage — variable collections are not supported!
  - use `tf.contrib.summary`
  - use **`tfe.`**`Iterator` to iterate over datasets under eager execution
  - prefer object-oriented layers (e.g., `tf.layers.Dense`)
    - functional layers (e.g., `tf.layers.dense`) only work if wrapped in **`tfe.`**`make_template`
  - prefer **`tfe.`**`py_func` over `tf.py_func`

- See the user guide for details and updates

What if I like graphs?

Graphs are ...

- Optimizable
  - automatic buffer reuse
  - constant folding
  - inter-op parallelism
  - automatic trade-off between compute and memory
- Deployable
  - the Graph is an *intermediate representation* for models
- Rewritable
  - experiment with automatic device placement or quantization

Imperative to declarative and back

- **Write model definition code once**
  - The same code can execute operations in one Python process and construct graphs in another (see user guide/examples)

- **Checkpoints are compatible**
  - Train eagerly, checkpoint, load in a graph, or vice-versa

- **Create graphs while eager execution is enabled**:
  - `@tfe.function`: "Compile" computation into graphs

So when should I use eager execution?

Use eager if you're ...

- **a researcher and want a flexible framework**
  - python control flow and data structures enable experimentation
- **developing a new model**
  - immediate error reporting simplifies debugging
- **new to TensorFlow**
  - eager execution lets you explore the TF API in the Python REPL

Note: In TF 2.0, eager execution will be enabled by default.

Status

- Available in version 1.5 of TensorFlow (`import tf.contrib.eager as tfe`)
- Single GPU, ResNet benchmark performance comparable to graphs
- Under active development
  - Overheads on smaller operations are significant
  - Distributed support is in the works
  - Not all TF APIs are eager-compatible

Further reading

Read the user guide to learn about ...

- High-level, Keras-like APIs for constructing models
  - `tfe.Network, tf.layers.Layer`
- Checkpointing variables
- Summaries and tensorboard
- Custom gradients for numerical stability
- Using GPUs

Check out the examples folder for idiomatic code

Links

- Paper
- Research blog post
- README
- User guide
- Idiomatic model examples
- Survey paper on autodiff for machine learning
- Github issues page
  - Found a bug? Want a feature? Create an issue!
- Feedback: akshayka@cs.stanford.edu

Next class

Variable sharing

Manage experiments

Autodiff

Feedback: huyenn@stanford.edu

Thanks!