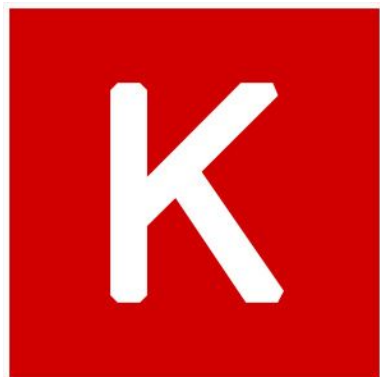


TensorFlow Tutorial

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Deep-Learning Package Zoo

- Torch
- Caffe
- Theano (Keras, Lasagne)
- CuDNN
- Tensorflow
- Mxnet
- Etc.



Deep-Learning Package Design Choices

- Model specification: **Configuration file** (e.g. Caffe, DistBelief, CNTK) versus **programmatic generation** (e.g. Torch, Theano, Tensorflow)
- For programmatic models, choice of high-level language: Lua (Torch) vs. Python (Theano, Tensorflow) vs others.
- We chose to work with **python** because of rich community and library infrastructure.

TensorFlow vs. Theano

- Theano is another deep-learning library with python-wrapper (was inspiration for Tensorflow)
- Theano and TensorFlow are very similar systems.
TensorFlow has better support for distributed systems though, and has development funded by Google, while Theano is an academic project.

What is TensorFlow?

- TensorFlow is a deep learning library recently open-sourced by Google.
- But what does it actually do?
 - TensorFlow provides primitives for defining functions on tensors and automatically computing their derivatives.



But what's a Tensor?

- Formally, tensors are multilinear maps from vector spaces to the real numbers (V vector space, and V^* dual space)

$$f : \underbrace{V^* \times \dots \times V^*}_{p \text{ copies}} \times \underbrace{V \times \dots \times V}_{q \text{ copies}} \rightarrow \mathbb{R}$$

- A scalar is a tensor ($f : \mathbb{R} \rightarrow \mathbb{R}, f(e_1) = d$)
- A vector is a tensor ($f : \mathbb{R}^n \rightarrow \mathbb{R}, f(e_i) = v_i$)
- A matrix is a tensor ($f : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}, f(e_i, e_j) = A_{ij}$)
- Common to have fixed basis, **so a tensor can be represented as a multidimensional array of numbers.**

TensorFlow vs. Numpy

- Few people make this comparison, but TensorFlow and Numpy are quite similar. (Both are N-d array libraries!)
- Numpy has N-d array support, but doesn't offer methods to create tensor functions and automatically compute derivatives (+ no GPU support).



VS



Simple Numpy Recap

```
In [23]: import numpy as np
```

```
In [24]: a = np.zeros((2,2)); b = np.ones((2,2))
```

```
In [25]: np.sum(b, axis=1)
```

```
Out[25]: array([ 2.,  2.])
```

```
In [26]: a.shape
```

```
Out[26]: (2, 2)
```

```
In [27]: np.reshape(a, (1,4))
```

```
Out[27]: array([[ 0.,  0.,  0.,  0.]])
```


Repeat in TensorFlow

More on *Session*
soon

```
In [31]: import tensorflow as tf
```

```
In [32]: tf.InteractiveSession()
```

```
In [33]: a = tf.zeros((2,2)); b = tf.ones((2,2))
```

```
In [34]: tf.reduce_sum(b, reduction_indices=1).eval()
```

```
Out[34]: array([ 2.,  2.], dtype=float32)
```

More on *.eval()*
in a few slides

```
In [35]: a.get_shape()
```

```
Out[35]: TensorShape([Dimension(2), Dimension(2)])
```

TensorShape behaves
like a python tuple.

```
In [36]: tf.reshape(a, (1, 4)).eval()
```

```
Out[36]: array([[ 0.,  0.,  0.,  0.]], dtype=float32)
```

Numpy to TensorFlow Dictionary

Numpy	TensorFlow
<code>a = np.zeros((2,2)); b = np.ones((2,2))</code>	<code>a = tf.zeros((2,2)), b = tf.ones((2,2))</code>
<code>np.sum(b, axis=1)</code>	<code>tf.reduce_sum(a, reduction_indices=[1])</code>
<code>a.shape</code>	<code>a.get_shape()</code>
<code>np.reshape(a, (1,4))</code>	<code>tf.reshape(a, (1,4))</code>
<code>b * 5 + 1</code>	<code>b * 5 + 1</code>
<code>np.dot(a,b)</code>	<code>tf.matmul(a, b)</code>
<code>a[0,0], a[:,0], a[0,:]</code>	<code>a[0,0], a[:,0], a[0,:]</code>

TensorFlow requires explicit evaluation!

```
In [37]: a = np.zeros((2,2))
```

```
In [38]: ta = tf.zeros((2,2))
```

```
In [39]: print(a)
```

```
[[ 0.  0.]  
 [ 0.  0.]]
```

```
In [40]: print(ta)
```

```
Tensor("zeros_1:0", shape=(2, 2), dtype=float32)
```

```
In [41]: print(ta.eval())
```

```
[[ 0.  0.]  
 [ 0.  0.]]
```

*TensorFlow computations define a **computation graph** that has no numerical value until evaluated!*

TensorFlow Session Object (1)

- “A Session object encapsulates the environment in which Tensor objects are evaluated” - [TensorFlow Docs](#)

```
In [20]: a = tf.constant(5.0)
```

```
In [21]: b = tf.constant(6.0)
```

```
In [22]: c = a * b
```

```
In [23]: with tf.Session() as sess:
        ....:     print(sess.run(c))
        ....:     print(c.eval())
        ....:
```

```
30.0
```

```
30.0
```

c.eval() is just syntactic sugar for sess.run(c) in the currently active session!

TensorFlow Session Object (2)

- `tf.InteractiveSession(s)` just convenient syntactic sugar for keeping a default session open in ipython.
- `sess.run(c)` is an example of a TensorFlow *Fetch*. Will say more on this soon.

Tensorflow Computation Graph

- “TensorFlow programs are usually structured into a construction phase, that assembles a graph, and an execution phase that uses a session to execute ops in the graph.” - [TensorFlow docs](#)
- All computations add nodes to global default graph ([docs](#))

TensorFlow Variables (1)

- “When you train a model you use variables to hold and update parameters. Variables are in-memory buffers containing tensors” - [TensorFlow Docs](#).
- All tensors we’ve used previously have been *constant* tensors, not variables.

TensorFlow Variables (2)

```
In [32]: W1 = tf.ones((2,2))
```

```
In [33]: W2 = tf.Variable(tf.zeros((2,2)), name="weights")
```

```
In [34]: with tf.Session() as sess:
          print(sess.run(W1))
          sess.run(tf.initialize_all_variables())
          print(sess.run(W2))
```

```
.....:
[[ 1.  1.]
 [ 1.  1.]]
[[ 0.  0.]
 [ 0.  0.]]
```



Note the initialization step `tf.initialize_all_variables()`

TensorFlow Variables (3)

- TensorFlow variables must be initialized before they have values! Contrast with constant tensors.

```
In [38]: W = tf.Variable(tf.zeros((2,2)), name="weights")
```

Variable objects can be initialized from constants or random values

```
In [39]: R = tf.Variable(tf.random_normal((2,2)), name="random_weights")
```

```
In [40]: with tf.Session() as sess:
.....:     sess.run(tf.initialize_all_variables())
.....:     print(sess.run(W))
.....:     print(sess.run(R))
.....:
```

Initializes all variables with specified values.

Updating Variable State

In [63]: `state = tf.Variable(0, name="counter")`

In [64]: `new_value = tf.add(state, tf.constant(1))` — *Roughly $new_value = state + 1$*

In [65]: `update = tf.assign(state, new_value)` — *Roughly $state = new_value$*

In [66]: `with tf.Session() as sess:`
 `....: sess.run(tf.initialize_all_variables())`
 `....: print(sess.run(state))`
 `....: for _ in range(3):` ← *Roughly*
 `....: sess.run(update)` *$state = 0$*
 `....: print(sess.run(state))` *$print(state)$*
 `....:` *$for _ in range(3):$*
 `....: state = state + 1` *$state = state + 1$*
 `....: print(state)` *$print(state)$*

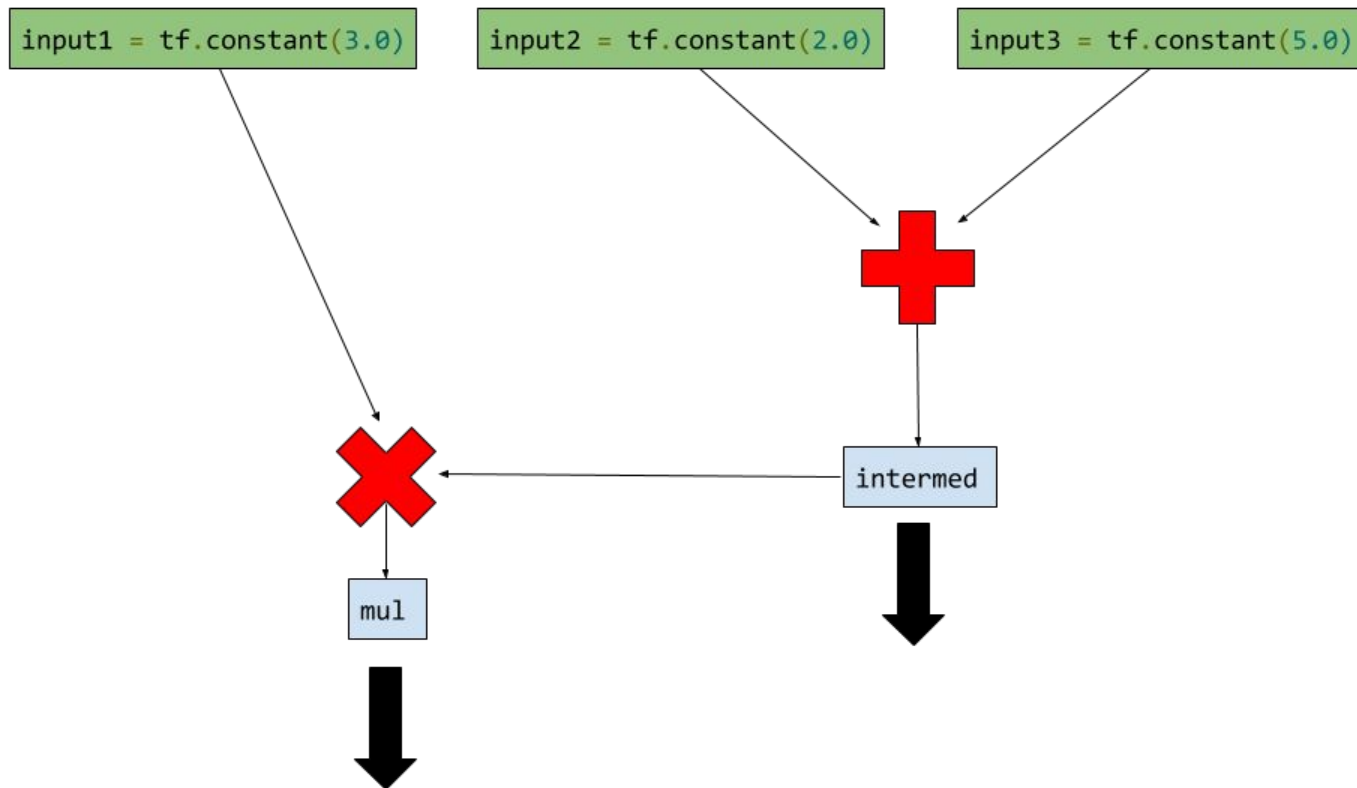
0
1
2
3

Fetching Variable State (1)

```
In [82]: input1 = tf.constant(3.0)
In [83]: input2 = tf.constant(2.0)
In [84]: input3 = tf.constant(5.0)
In [85]: intermed = tf.add(input2, input3)
In [86]: mul = tf.mul(input1, intermed)
In [87]: with tf.Session() as sess:
.....:     result = sess.run([mul, intermed])
.....:     print(result)
.....:
[21.0, 7.0]
```

Calling `sess.run(var)` on a `tf.Session()` object retrieves its value. Can retrieve multiple variables simultaneously with `sess.run([var1, var2])` (See *Fetches* in TF docs)

Fetching Variable State (2)



Inputting Data

- All previous examples have manually defined tensors.
How can we input external data into TensorFlow?
- Simple solution: Import from Numpy:

```
In [93]: a = np.zeros((3,3))
In [94]: ta = tf.convert_to_tensor(a)
In [95]: with tf.Session() as sess:
.....:     print(sess.run(ta))
.....:
[[ 0.  0.  0.]
 [ 0.  0.  0.]
 [ 0.  0.  0.]
```

Placeholders and Feed Dictionaries (1)

- Inputting data with `tf.convert_to_tensor` is convenient, but doesn't scale.
- Use `tf.placeholder` variables (dummy nodes that provide entry points for data to computational graph).
- A `feed_dict` is a python dictionary mapping from `tf.placeholder`s (or their names) to data (numpy arrays, lists, etc.).

Placeholders and Feed Dictionaries (2)

```
In [96]: input1 = tf.placeholder(tf.float32)
```

```
In [97]: input2 = tf.placeholder(tf.float32)
```

```
In [98]: output = tf.mul(input1, input2)
```

```
In [99]: with tf.Session() as sess:  
.....:     print(sess.run([output], feed_dict={input1:[7.], input2:[2.]}))  
.....:
```

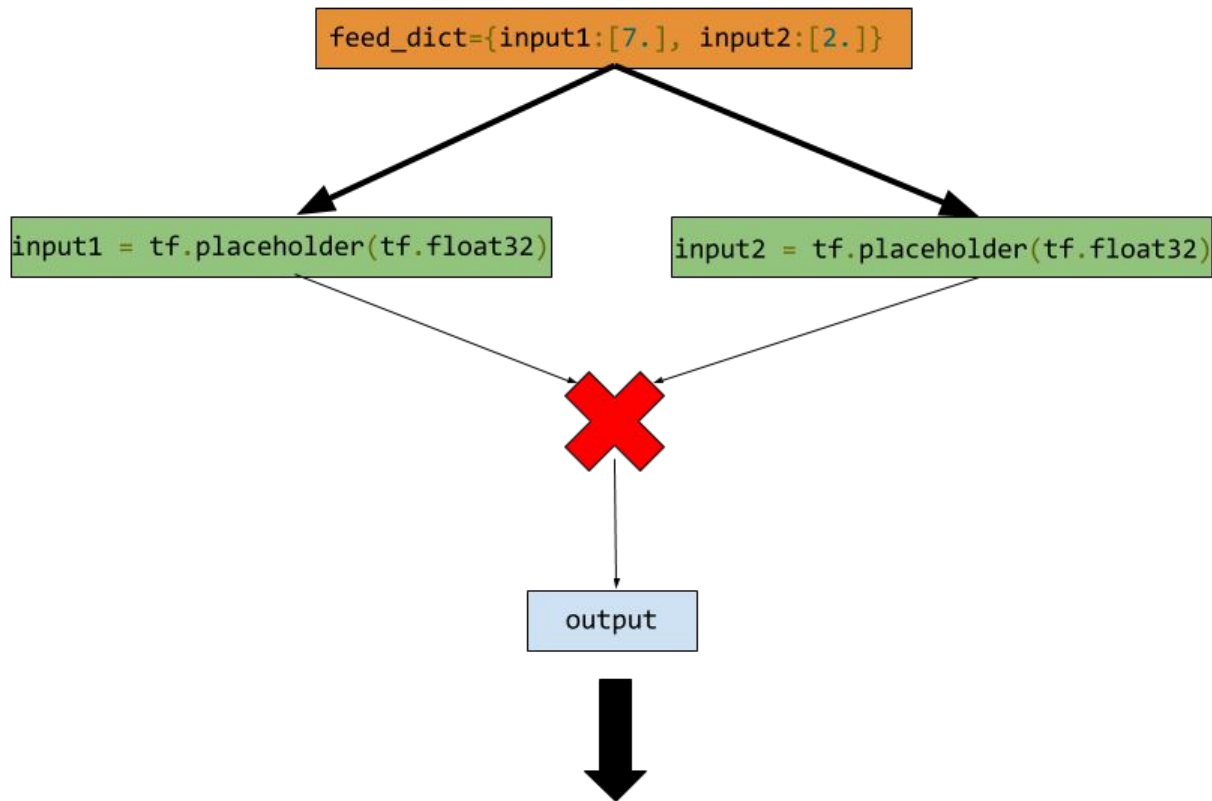
```
[array([ 14.], dtype=float32)]
```

*Define tf.placeholder
objects for data entry.*

*Fetch value of output
from computation graph.*

*Feed data into
computation graph.*

Placeholders and Feed Dictionaries (3)



Variable Scope (1)

- Complicated TensorFlow models can have hundreds of variables.
 - `tf.variable_scope()` provides simple name-spacing to avoid clashes.
 - `tf.get_variable()` creates/accesses variables from within a variable scope.

Variable Scope (2)

- Variable scope is a simple type of namespacing that adds prefixes to variable names within scope

```
with tf.variable_scope("foo"):  
    with tf.variable_scope("bar"):  
        v = tf.get_variable("v", [1])  
assert v.name == "foo/bar/v:0"
```

Variable Scope (3)

- Variable scopes control variable (re)use

```
with tf.variable_scope("foo"):  
    v = tf.get_variable("v", [1])  
    tf.get_variable_scope().reuse_variables()  
    v1 = tf.get_variable("v", [1])  
assert v1 == v
```

- You'll need to use ***reuse_variables()*** to implement RNNs in homework

Understanding get_variable (1)

- Behavior depends on whether variable reuse enabled
- **Case 1:** reuse set to false
 - Create and return new variable

```
with tf.variable_scope("foo"):  
    v = tf.get_variable("v", [1])  
assert v.name == "foo/v:0"
```

Understanding get_variable (2)

- **Case 2:** Variable reuse set to true
 - Search for existing variable with given name. Raise **ValueError** if none found.

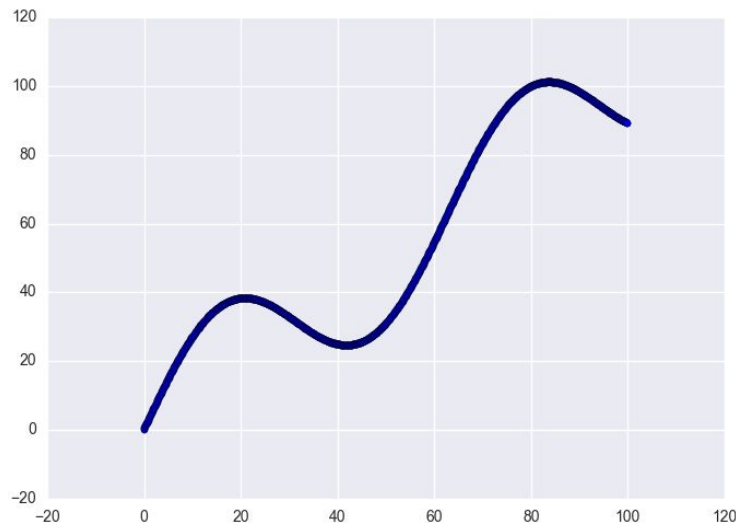
```
with tf.variable_scope("foo"):
    v = tf.get_variable("v", [1])
with tf.variable_scope("foo", reuse=True):
    v1 = tf.get_variable("v", [1])
assert v1 == v
```

Ex: Linear Regression in TensorFlow (1)

```
import numpy as np
import seaborn

# Define input data
X_data = np.arange(100, step=.1)
y_data = X_data + 20 * np.sin(X_data/10)

# Plot input data
plt.scatter(X_data, y_data)
```



Ex: Linear Regression in TensorFlow (2)

```
# Define data size and batch size
```

```
n_samples = 1000
```

```
batch_size = 100
```

```
# Tensorflow is finicky about shapes, so resize
```

```
X_data = np.reshape(X_data, (n_samples,1))
```

```
y_data = np.reshape(y_data, (n_samples,1))
```

```
# Define placeholders for input
```

```
X = tf.placeholder(tf.float32, shape=(batch_size, 1))
```

```
y = tf.placeholder(tf.float32, shape=(batch_size, 1))
```

Ex: Linear Regression in TensorFlow (3)

Define variables to be learned

```
with tf.variable_scope("linear-regression"):
```

```
    W = tf.get_variable("weights", (1, 1),  
                        initializer=tf.random_normal_initializer())
```

```
    b = tf.get_variable("bias", (1,),  
                        initializer=tf.constant_initializer(0.0))
```

```
y_pred = tf.matmul(X, W) + b
```

```
loss = tf.reduce_sum((y - y_pred)**2/n_samples)
```

Note `reuse=False` so
these tensors are
created anew

$$J(W, b) = \frac{1}{N} \sum_{i=1}^N (y_i - (Wx_i + b))^2$$

Ex: Linear Regression in TensorFlow (4)

Sample code to run one step of gradient descent

In [136]: `opt = tf.train.AdamOptimizer()`

In [137]: `opt_operation = opt.minimize(loss)`

Note TensorFlow scope is not python scope! Python variable `loss` is still visible.

In [138]: `with tf.Session() as sess:`

`.....: sess.run(tf.initialize_all_variables())`

`.....: sess.run([opt_operation], feed_dict={X: X_data, y: y_data})`

`.....:`

But how does this actually work under the hood? Will return to TensorFlow computation graphs and explain.

Ex: Linear Regression in TensorFlow (4)

Sample code to run full gradient descent:

Define optimizer operation

```
opt_operation = tf.train.AdamOptimizer().minimize(loss)
```

```
with tf.Session() as sess:
```

```
    # Initialize Variables in graph
```

```
    sess.run(tf.initialize_all_variables())
```

```
    # Gradient descent loop for 500 steps
```

```
    for _ in range(500):
```

```
        # Select random minibatch
```

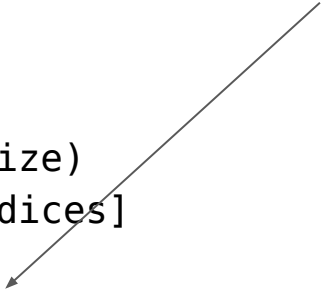
```
        indices = np.random.choice(n_samples, batch_size)
```

```
        X_batch, y_batch = X_data[indices], y_data[indices]
```

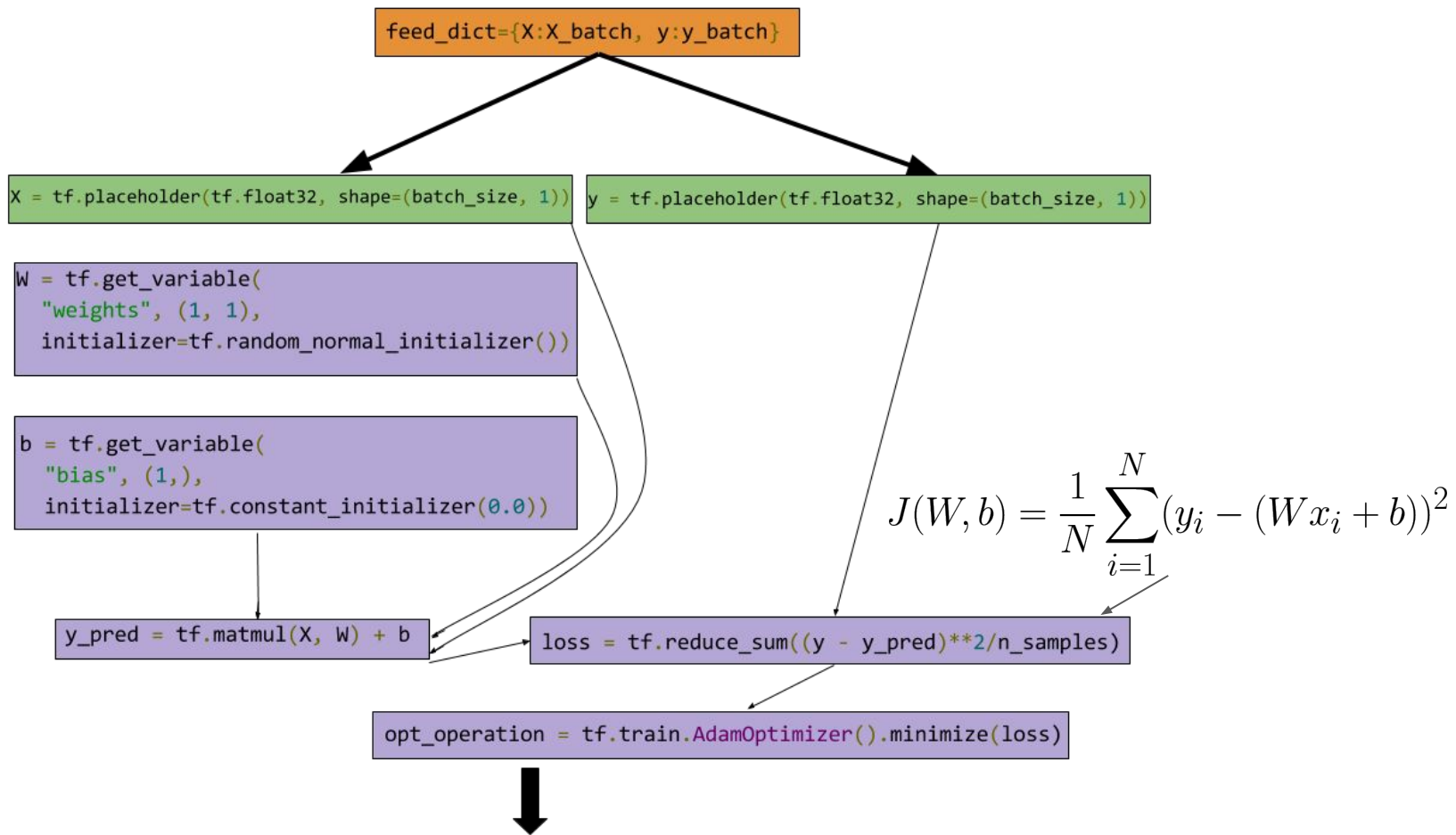
```
        # Do gradient descent step
```

```
        _, loss_val = sess.run([opt_operation, loss], feed_dict={X: X_batch, y: y_batch})
```

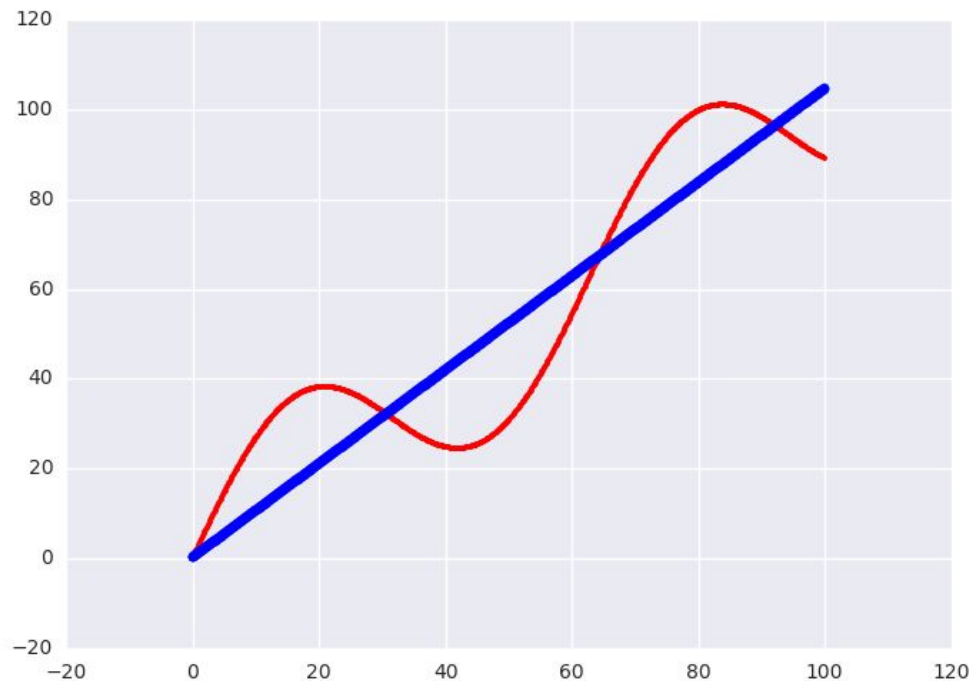
*Let's do a deeper.
graphical dive into
this operation*



Ex: Linear Regression in TensorFlow (5)



Ex: Linear Regression in TensorFlow (6)



← *Learned model offers nice fit to data.*

Concept: Auto-Differentiation

- Linear regression example computed L2 loss for a linear regression system. How can we fit model to data?
 - `tf.train.Optimizer` creates an optimizer.
 - `tf.train.Optimizer.minimize(loss, var_list)` adds optimization operation to computation graph.
- Automatic differentiation computes gradients without user input!

TensorFlow Gradient Computation

- TensorFlow nodes in computation graph have attached gradient operations.
- Use backpropagation (using node-specific gradient ops) to compute required gradients for all variables in graph.

TensorFlow Gotchas/Debugging (1)

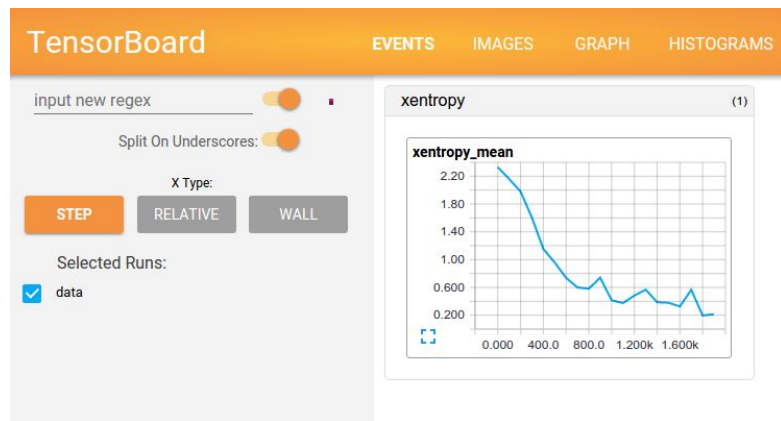
- Convert tensors to numpy array and print.
- TensorFlow is fastidious about types and shapes. Check that types/shapes of all tensors match.
- TensorFlow API is less mature than Numpy API. Many advanced Numpy operations (e.g. complicated array slicing) not supported yet!

TensorFlow Gotchas/Debugging (2)

- If you're stuck, try making a pure Numpy implementation of forward computation.
- Then look for analog of each Numpy function in TensorFlow API
- Use `tf.InteractiveSession()` to experiment in shell. Trial and error works!

TensorBoard

- TensorFlow has some neat built-in visualization tools (TensorBoard).
- We won't use TensorBoard for homework (tricky to set up when TensorFlow is running remotely), but we encourage you to check it out for your projects.



TensorFlow at Stanford

- CPU-only version of TensorFlow now available on a number of Stanford clusters (Corn, Myth)
- GPU versions of TensorFlow available only on limited clusters (Sherlock, Xstream). Feel free to use if you already have access.
- CPU-only version sufficient for homework (but will be slower than GPU version)

Hint for HW: Defining Embeddings in TensorFlow

```
# Define Placeholders for inputs
```

```
train_inputs = tf.placeholder(tf.int32, shape=[batch_size])
```

```
train_labels = tf.placeholder(tf.int32, shape=[batch_size, 1])
```

```
# Look up embeddings for inputs.
```

```
# You'll use this for PSet 2
```

```
embeddings = tf.Variable(
```

```
    tf.random_uniform([vocabulary_size, embedding_size], -1.0, 1.0))
```

```
embed = tf.nn.embedding_lookup(embeddings, train_inputs)
```