Deep Learning Practice with Caffe

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Intel

Slides & Example Codes

- https://github.com/kyehyeon/caffe-materials
  - Click 

Contents

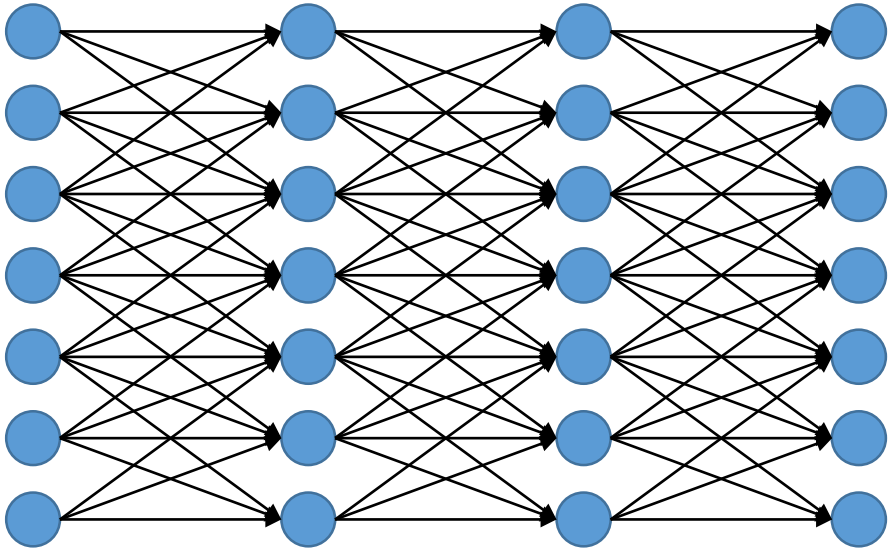
- Caffe?
- Installation
- Getting started: Image classification
  - Network design → Data preparation → Training → Testing
- More examples
  - Python interface usages
  - Advanced building blocks
  - Layer implementation

Caffe?

- Lots of DL libraries…
  - TensorFlow, Caffe, Theano-based (Keras, Lasagne, Pylearn, …), Torch, CuDNN, mxnet, neon, Intel MKL DL, …
- Caffe
  - **[△]** Rapid prototyping in an algorithmic level (a new layer, new loss function, …)
  - **[X]** Multi-device support
  - **[X]** Easy installation & Portability
  - **[△]** Documentation
  - **[◯]** Rapid tuning by trial & error
  - **[◯]** Fast
  - **[◯]** Best support for computer vision research with large-scale datasets
  - **[◯]** Portability of networks & pre-trained models: Highly reproducible

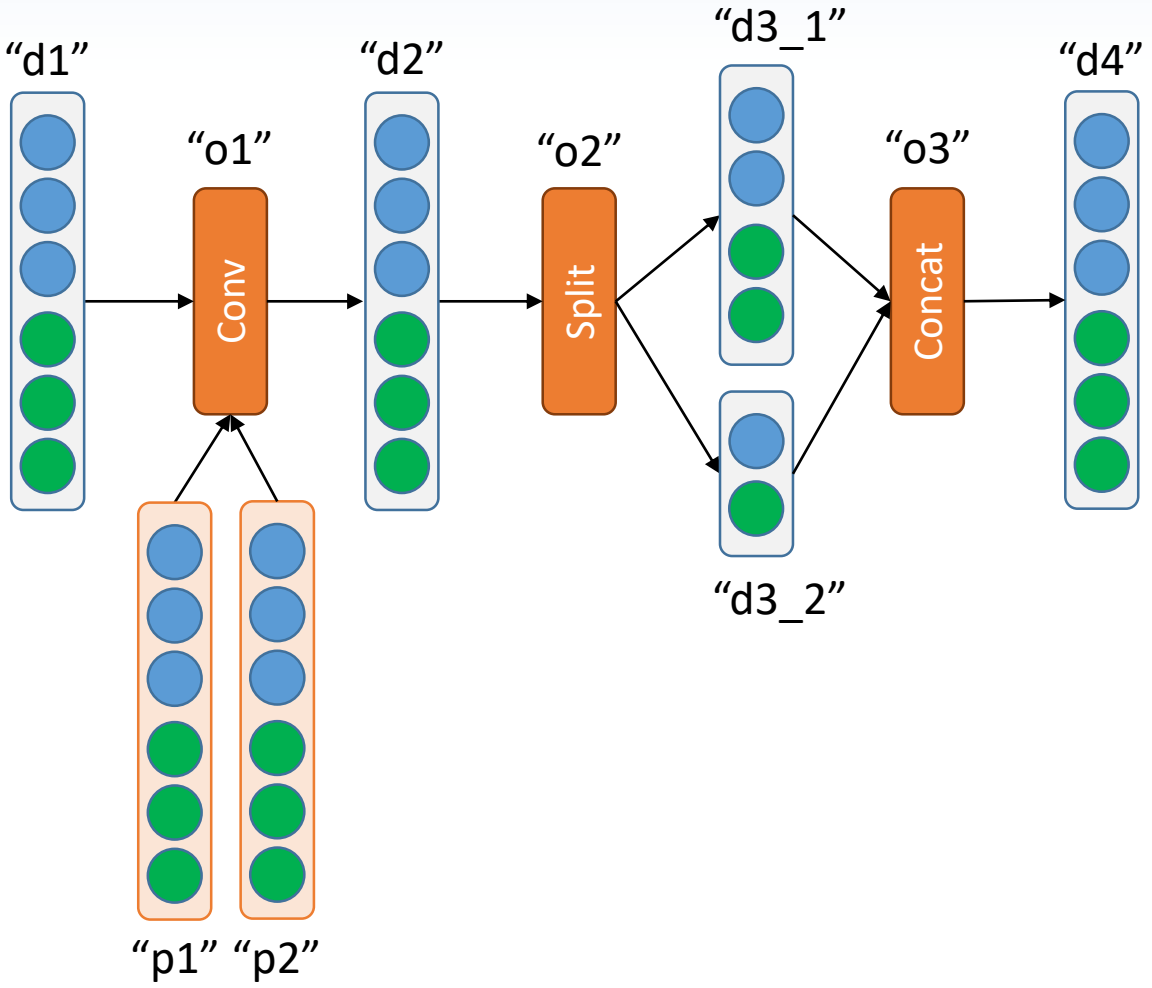
Classical Deep Network Representation

- Layer = data
- Connection = parameter
- Do **not** think like this



Deep Network Representation in DL Libraries

- Layer = operator
  - May or **may not** mathematical function
  - May or **may not** have trainable parameters
- Blob = data, parameter
  - Values & Gradients
- Connection = data flow



Prototxt

- Spec document for a network
- **layer { … }:** Layer
  - **name:** Layer's name
  - **type:** Operation
  - **bottom:** Input data name
    - Repeatable (multi-input)
  - **top:** Output data name
    - Repeatable (multi-output)
  - **param { … }:** Trainable parameter
    - Repeatable (e.g., weight, bias, …)
  - **xxx_param { … }:** Options for operation 'xxx'

```
layer {
  name: "conv1/conv"
  type: "Convolution"
  bottom: "data"
  top: "conv1"
  param { name: "conv1/conv_weight"  lr_mult: 0.1 }
  param { name: "conv1/conv_bias"  lr_mult: 0.1 }
  convolution_param {
    num_output: 64  kernel_size: 3  stride: 2  pad: 1
    weight_filler { type: "xavier" }
    bias_filler { type: "constant" value: 0.1 }
  }
}
layer {
  name: "conv1/relu"
  type: "ReLU"
  bottom: "conv1"
  top: "conv1"
}
layer {
  name: "pool1/pool"
  type: "Pooling"
  bottom: "conv1"
  top: "pool1"
  pooling_param {
    pool: MAX
    kernel_size: 3  stride: 2
  }
}
```

Prototxt

- Major difference between Caffe and other libs
- { network structure, data } ==x x== { code, platform }
  - Easy to read & maintain
  - Easy to fix & retry
  - Reproducible
  - Portable
  - Forward/backward compatible

Installation

Installation Methods

- http://caffe.berkeleyvision.org/installation.html
- Windows
  - Docker: Not support GPU mode
  - Caffe for Windows
    - Require Visual Studio 2013 (+ NVIDIA driver & CUDA-7.5 for GPU mode)
    - Hard to follow-up latest updates
  - Linux subsystem (Windows 10 Redstone only): Not support GPU mode
- Ubuntu
  - Docker: Recommended method
  - Native installation: Also recommended, but takes too much time to practice
  - Amazon web services (AWS)
    - Also recommended if you have money (~$1/hour for GPU machine)
    - Not support GPU mode on 12-month free-trial instances

Ubuntu + Docker: Overview

- Pre-requisites
  - Ubuntu 14.04
  - NVIDIA driver & CUDA-7.5 (for GPU mode)
- Steps
  - Install Docker
  - Install NVIDIA Docker (for GPU mode)
  - Build Caffe image & Create virtual machine

Ubuntu + Docker: Install Docker

- Open terminal & Follow installation instructions in https://docs.docker.com/engine/installation/linux/ubuntulinux/
- Test whether Docker is properly installed

```
$ sudo docker run hello-world
```

```
Hello from Docker!
This message shows that your installation appears to be working correctly.
...
```

```
$ sudo apt-get update
$ sudo apt-get install apt-transport-https ca-certificates

$ sudo apt-key adv --keyserver hkp://p80.pool.sks-keyservers.net:80 \
                   --recv-keys 58118E89F3A912897C070ADBF76221572C52609D

$ sudo bash -c \
    'echo "deb https://apt.dockerproject.org/repo ubuntu-trusty main" > \
     /etc/apt/sources.list.d/docker.list'

$ sudo apt-get update
$ sudo apt-get purge lxc-docker
$ apt-cache policy docker-engine
$ sudo apt-get update
$ sudo apt-get install linux-image-extra-$(uname -r)
$ sudo apt-get install apparmor
$ sudo apt-get update
$ sudo apt-get install docker-engine
$ sudo service docker start
```

Ubuntu + Docker: Install NVIDIA Docker

- Follow installation instructions for "Ubuntu distributions" in https://github.com/NVIDIA/nvidia-docker/wiki

```
$ wget -P /tmp https://github.com/NVIDIA/nvidia-docker/releases/download/v1.0.0-rc.3/nvidia-docker_1.0.0.rc.3-1_amd64.deb
$ sudo dpkg -i /tmp/nvidia-docker*.deb && rm /tmp/nvidia-docker*.deb
```

- Test whether nvidia-docker is properly installed

```
$ sudo nvidia-docker run --rm nvidia/cuda:7.5-devel nvcc --version
$ sudo nvidia-docker run --rm nvidia/cuda:7.5-devel nvidia-smi
```

```
nvcc: NVIDIA (R) Cuda compiler driver
Copyright (c) 2005-2015 NVIDIA Corporation
Built on Tue_Aug_11_14:27:32_CDT_2015
Cuda compilation tools, release 7.5, V7.5.17
```

- Numbers can be different

```
+-----------------------------------------------------+
| NVIDIA-SMI 352.93     Driver Version: 352.93        |
|-------------------------------+----------------------+----------------------+
| GPU  Name        Persistence-M| Bus-Id        Disp.A | Volatile Uncorr. ECC |
| Fan  Temp  Perf  Pwr:Usage/Cap|         Memory-Usage | GPU-Util  Compute M. |
...
```

- Numbers can be different, but you should see a table like this
- Otherwise, it means that NVIDIA driver is not properly installed

Ubuntu + Docker: Install NVIDIA Docker

- Follow installation instructions for "Ubuntu distributions" in https://github.com/NVIDIA/nvidia-docker/wiki

```
$ wget -P /tmp https://github.com/NVIDIA/nvidia-docker/releases/download/v1.0.0-rc.3/nvidia-docker_1.0.0.rc.3-1_amd64.deb
$ sudo dpkg -i /tmp/nvidia-docker*.deb && rm /tmp/nvidia-docker*.deb
```

- Test whether nvidia-docker is properly installed

```
$ sudo nvidia-docker run --rm nvidia/cuda:7.5-devel nvcc --version
$ sudo nvidia-docker run --rm nvidia/cuda:7.5-devel nvidia-smi
```

```
docker and nvidia-docker require root permission (sudo)
nvidia-docker run initiates a container (VM) from a pre-built image, and then executes a command on it
  nvidia/cuda:7.5-devel: Pre-built image. If it doesn't exist in the host machine,
                         search & download it from Docker Hub (https://hub.docker.com)
  nvidia-smi: command to be executed
--name <container name> option assigns the name to the container, which is omitted in the above example
--rm option removes the container after the command is finished
```

Ubuntu + Docker: Build Caffe Image (GPU)

- Open gedit & Write Dockerfile

```
$ gedit Dockerfile
```

- Build image named caffe-img

```
$ sudo nvidia-docker build -t caffe-img .
```

- Permission settings for GUI

```
$ echo "xhost +SI:localuser:root" >> ~/.profile
$ xhost +SI:localuser:root
```

```
FROM kaixhin/cuda-caffe
RUN apt-get update
RUN apt-get install -y x11-apps python-tk tk-dev vim
RUN pip uninstall -y matplotlib
RUN pip install matplotlib
ENV DISPLAY :0
RUN echo "export PATH=:/root/caffe/build/tools:\${PATH}" >> ~/.bashrc
RUN echo "export LD_LIBRARY_PATH=:/root/caffe/build/lib:\${LD_LIBRARY_PATH}" >> ~/.bashrc
RUN cp /root/caffe/Makefile.config.example /root/caffe/Makefile.config
RUN echo "USE_CUDNN := 1" >> /root/caffe/Makefile.config
RUN cd /root/caffe
RUN git pull origin master
RUN make clean
RUN make -j"$(nproc)" all && make pycaffe
```

Ubuntu + Docker: Build Caffe Image (CPU)

- Open gedit & Write Dockerfile

```
$ gedit Dockerfile
```

- Build image named caffe-img

```
$ sudo docker build -t caffe-img .
```

- Permission settings for GUI

```
$ echo "xhost +SI:localuser:root" >> ~/.profile
$ xhost +SI:localuser:root
```

```
FROM kaixhin/caffe
RUN apt-get update
RUN apt-get install -y x11-apps python-tk tk-dev vim
RUN pip uninstall -y matplotlib
RUN pip install matplotlib
ENV DISPLAY :0
RUN echo "export PATH=:/root/caffe/build/tools:\${PATH}" >> ~/.bashrc
RUN echo "export LD_LIBRARY_PATH=:/root/caffe/build/lib:\${LD_LIBRARY_PATH}" >> ~/.bashrc
RUN cp /root/caffe/Makefile.config.example /root/caffe/Makefile.config
RUN echo "CPU_ONLY := 1" >> /root/caffe/Makefile.config
RUN cd /root/caffe
RUN git pull origin master
RUN make clean
RUN make -j"$(nproc)" all && make pycaffe
```

GPU vs. CPU: Only two lines are different!

```
FROM kaixhin/cuda-caffe
...
RUN echo "USE_CUDNN := 1" >> ...
```

```
FROM kaixhin/caffe
...
RUN echo "CPU_ONLY := 1" >> ...
```

Ubuntu + Docker: Caffe VM

CPU-only mode:
Replace nvidia-docker → docker

- Create virtual machine named caffe

```
$ sudo nvidia-docker run -tid \
                         -v /tmp/.X11-unix:/tmp/.X11-unix \
                         -v /tmp/.docker.xauth:/tmp/.docker.xauth \
                         -e XAUTHORITY=/tmp/.docker.xauth \
                         --name caffe caffe-img
```

t: Enable terminal mode
i: Get standard input (interactive mode)
d: Run on background

} Options for GUI

- Open terminal on the VM

```
$ sudo nvidia-docker exec -ti caffe bash
```

```
$ sudo nvidia-docker exec -ti caffe bash   // Start terminal
    root@...:~/caffe#       // Now you are in VM as root
    ... do some work ...
    root@...:~/caffe# exit  // End terminal
$ sudo nvidia-docker stop caffe         // Power-off VM
$ sudo nvidia-docker start caffe        // Power on VM
$ sudo nvidia-docker commit caffe caffe_160819  // Backup VM
$ sudo nvidia-docker rm caffe           // Remove VM
$ sudo nvidia-docker rmi caffe-img      // Remove image
```

Ubuntu + Docker: Caffe VM

- Test Caffe on the VM

```
~/caffe# ./data/cifar10/get_cifar10.sh
~/caffe# ./examples/cifar10/create_cifar10.sh
~/caffe# ./examples/cifar10/train_quick.sh
```

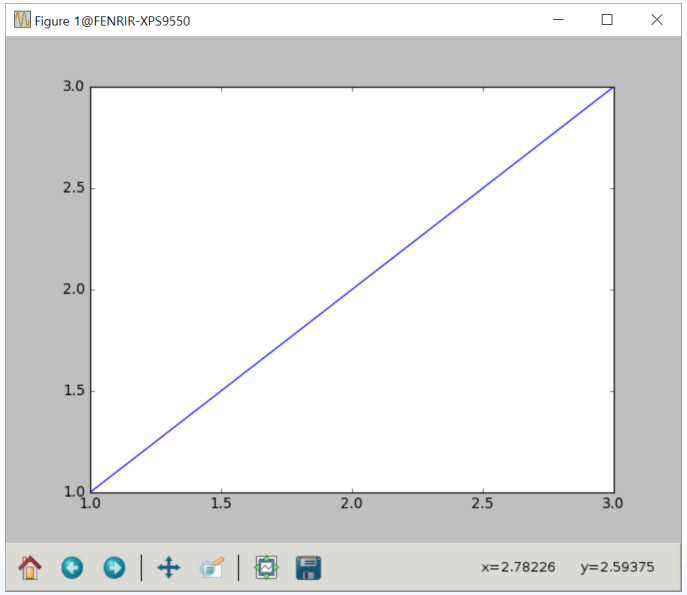
CPU-only mode: Edit solver_mode: **GPU** → solver_mode: **CPU**
in ./examples/cifar10/cifar10_quick_solver.prototxt

```
libdc1394 error: Failed to initialize libdc1394
...
I08… solver.cpp:317] Iteration 5000, loss = 0.584047
I08… solver.cpp:337] Iteration 5000, Testing net (#0)
I08… solver.cpp:404]     Test net output #0: accuracy = 0.7587
I08… solver.cpp:404]     Test net output #1: loss = 0.723281 (* 1 = 0.723281 loss)
I08… solver.cpp:322] Optimization Done.
I08… caffe.cpp:254] Optimization Done.
```

- Numbers can be different
- In CPU mode, every 100-iteration takes around 1 minute or more
- In GPU mode, every 100-iteration should be done in a few seconds, and the whole training process should be finished in several minutes. Otherwise, it means that CUDA doesn't work, mostly because NVIDIA driver is not properly installed

- Test GUI on the VM

```
~/caffe# python
>>> import matplotlib.pyplot as plt
>>> plt.plot([1,2,3], [1,2,3])
>>> plt.show()
```



- UI can be different, but you should see a figure like this

Windows: Docker

- https://github.com/BVLC/caffe/tree/master/docker
- Support CPU mode only
- Install Docker
  - Windows 10 Pro
    https://docs.docker.com/docker-for-windows/
  - Other Windows
    https://www.docker.com/products/docker-toolbox

- Virtualization
  - Check taskmgr → 성능 → "가상화: 사용"
  - If not, modify your BIOS settings
  - e.g., Advanced → CPU → Virtualization
- File sharing with host machine
  - Right click Docker icon in Taskbar
    → Click "Settings…"
  - Click "Shared drives"
    → Select drive you want to share
    → Click "Apply"
    → Enter your Windows account info

Windows: Docker

```
C:\...> docker pull kaixhin/caffe    // Download Caffe dockerfile
C:\...> docker run -dit --name caffe kaixhin/caffe    // Create VM

C:\...> docker exec -ti caffe bash    // Start Linux terminal

  root@...:~/caffe#                   // Now you are in Linux VM

  ... do some work ...

  root@...:~/caffe# exit              // End Linux terminal

C:\...> docker stop caffe             // Power-off VM
C:\...> docker start caffe            // Power on VM

C:\...> docker commit caffe caffe_160819     // Backup VM

C:\...> docker rm caffe               // Remove VM
C:\...> docker rmi kaixhin/caffe      // Remove Caffe dockerfile
```

```
// Install other packages required in this lecture
...# apt-get update && apt-get upgrade
...# apt-get install python-opencv python-pip vim
...# pip install lmdb
...# git clone https://github.com/kyehyeon/caffe-materials

// Do only if arrow keys do not work in your vim
...# echo "set term=cons25" >> ~/.vimrc

// Get the latest Caffe
root@...:~/caffe# git pull origin master
root@...:~/caffe# make clean
root@...:~/caffe# cp Makefile.config.example Makefile.config
root@...:~/caffe# vim Makefile.config
    // Uncomment "CPU_ONLY := 1" and "WITH_PYTHON_LAYER := 1"
root@...:~/caffe# make -j"$(nproc)" all && make pycaffe
```

Other Options: Pre-requisites

- Visual Studio 2013 (for Windows)
- NVIDIA driver & CUDA 7.5 (for GPU mode)
  - https://developer.nvidia.com/cuda-downloads
  - Install NVIDIA driver: Yes (even if a newer version is already installed)
  - Install CUDA toolkit: Yes
  - CUDA toolkit path: Default
  - Make symbolic link: Yes
- CuDNN library (for GPU mode)
  - https://developer.nvidia.com/rdp/cudnn-download (membership required)
  - Download **v5** (not RC!) for CUDA **7.5**
  - Unzip & Remember CuDNN root path
    - Include path: <CuDNN root>/include
    - Library path: <CuDNN root>/lib64

Windows: Caffe for Windows

- https://github.com/BVLC/caffe/tree/windows
  - Click 

  - caffe-windows\windows
    CommonSettings.props.example → CommonSettings.props

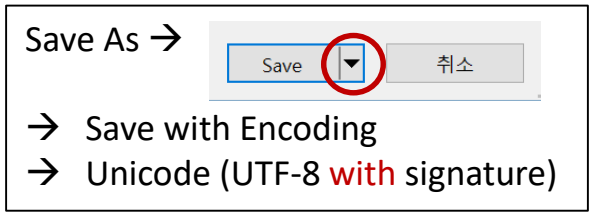
```
<CpuOnlyBuild>true</CpuOnlyBuild>
<UseCuDNN>false</UseCuDNN>
…
<PythonSupport>true</PythonSupport>
…
<PropertyGroup Condition="'$(PythonSupport)'=='true'">
    <PythonDir>your Miniconda path</PythonDir>
```

- Install Miniconda (Python + Libraries)
  - http://conda.pydata.org/miniconda.html
  - Download Python 2.7 & 64-bit & Install
    - Just for me, Add to path, Default Python
  - cmd → `conda install --yes numpy scipy matplotlib scikit-image pip lmdb`

Windows: Caffe for Windows

- Open caffe-windows\windows\Caffe.sln
- Build → Build Solution (F7)
  - caffe-windows\Build\x64\{Debug, Release}*.exe
  - Trouble shooting

```
warning C4819: The file contains a character that cannot be represented in the current code page (949). Save the file in Unicode format to prevent data loss
```



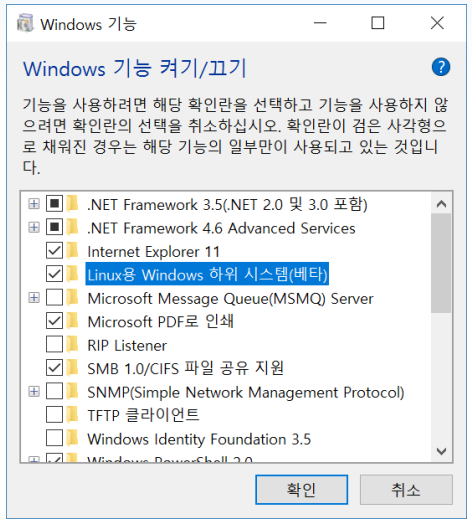
rng.hpp
alt_sstream_impl.hpp
opaque_pointer_converter.hpp
dealloc.hpp
return_opaque_pointer.hpp

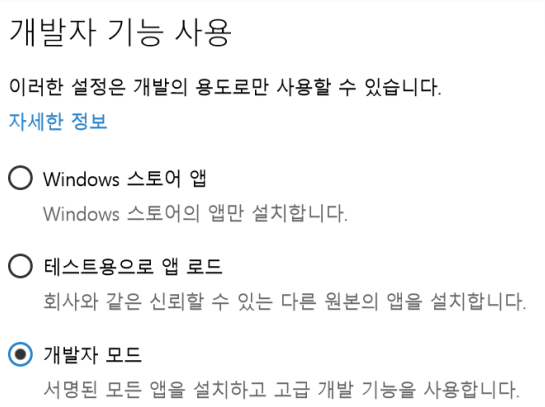
- Copy Python package
  - caffe-windows\Build\x64\{Debug, Release}\pycaffe\caffe
    → <Miniconda root>\Lib\site-packages

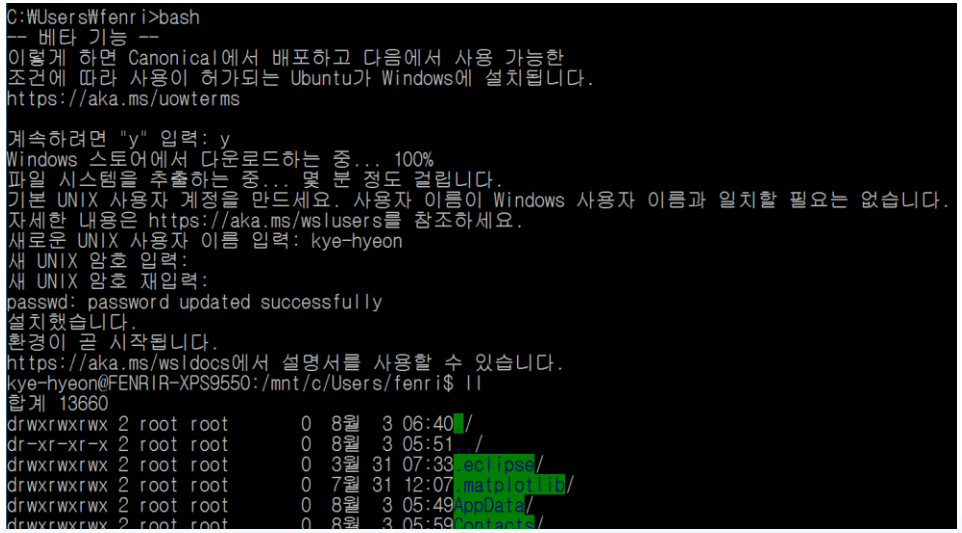
    C:\Users\<your account name>\Miniconda2

Windows: Linux Subsystem

- Install Linux subsystem
  - 제어판 → “프로그램 및 기능” → “Windows 기능 켜기/끄기” → “Linux용 Windows 하위 시스템(베타)”
  - 설정 → “업데이트 및 복구” → “개발자용” → “개발자 모드”
  - cmd → bash → “y <Enter>”
- Follow instructions in Ubuntu: Native Installation







Windows: Linux Subsystem

- Locale & GUI settings

```
$ sudo update-locale LANG=en_US.UTF8
$ vim ~/.bashrc
```

```
export DISPLAY=:0.0
```

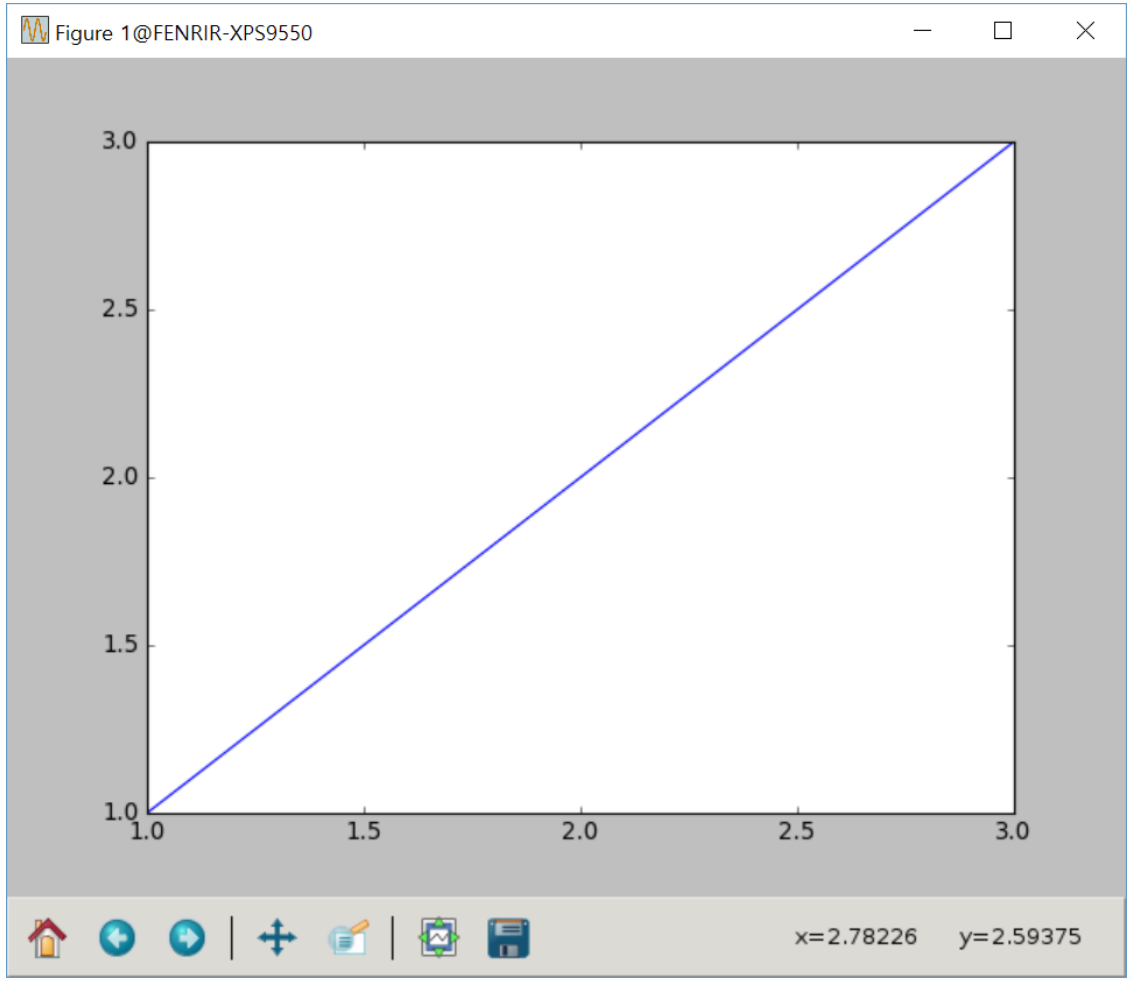
```
$ sudo vim /etc/dbus-1/session.conf
```

```
<listen>unix:tmpdir=/tmp</listen>
➔ <listen>tcp:host=localhost,port=0</listen>
```

```
$ sudo apt-get install python-tk tk-dev
$ pip uninstall -y matplotlib
$ pip install --user matplotlib
```

```
$ python
```

```
>>> import matplotlib.pyplot as plt
>>> plt.plot([1,2,3], [1,2,3])
>>> plt.show()
```



Ubuntu: Native Installation

- http://caffe.berkeleyvision.org/install_apt.html
- Install pre-built packages

```
$ sudo apt-get update
$ sudo apt-get install <following packages>
```

```
build-essential git
libprotobuf-dev protobuf-compiler libhdf5-serial-dev
libgflags-dev libgoogle-glog-dev libsnappy-dev
libatlas-base-dev libopencv-dev
liblmdb-dev libleveldb-dev
python-dev python-pip python-opencv gfortran
```

```
$ sudo apt-get install --no-install-recommends libboost-all-dev
$ pip install --user easydict
$ pip install --user lmdb
```

Ubuntu: Native Installation

- Download Caffe & Install Python

```
$ git clone https://github.com/BVLC/caffe.git
$ cd caffe/python/
$ for req in $(cat requirements.txt); do pip install --user $req; done
$ pip install --user dask
$ for req in $(cat requirements.txt); do pip install --user $req; done   // To check successful installation
$ cd ..
$ git clone https://github.com/kyehyeon/caffe-materials
```

- Build Caffe

```
$ cp Makefile.config.example Makefile.config
$ vim Makefile.config
    // Uncomment "CPU_ONLY := 1" if you have no GPU
    // Uncomment "WITH_PYTHON_LAYER := 1"
$ make -j8 && make pycaffe
```

- Set paths

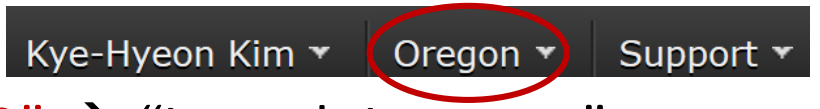
```
$ vim ~/.bashrc
```

```
export CAFFE_ROOT=<your Caffe root directory>
export PATH=:${CAFFE_ROOT}/build/tools:${PATH}
export LD_LIBRARY_PATH=:${CAFFE_ROOT}/build/lib:${LD_LIBRARY_PATH}
export PYTHONPATH=:${CAFFE_ROOT}/python:${PYTHONPATH}
```

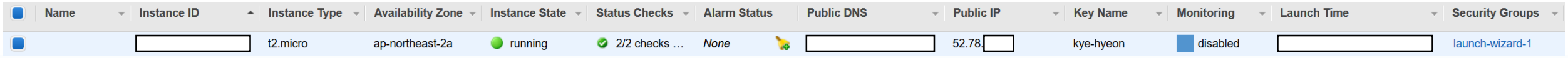
Ubuntu: AWS

- https://aws.amazon.com
- Join AWS
  - Click “Create a Free Account”
  - Sign in with your Amazon account
  - Select “Personal Account” & Follow the steps
  - Click “Sign In to the Console”

- Create AWS instance
  - Change region to “Asia Pacific (Tokyo)”



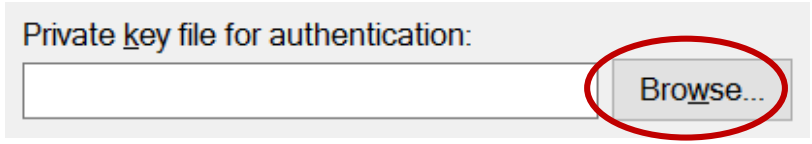
  - Click “EC2” → “Launch Instance”
  - Select “Ubuntu Server 14.04 LTS (HVM), SSD Volume Type” → “t2.micro” → “Review & Launch”
  - Create a new key pair → Any name → Save <your name>.pem file



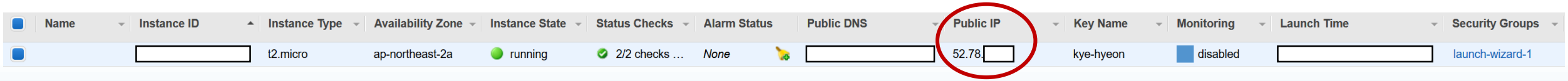
Ubuntu: AWS

- Download PuTTY and PuTTYgen
  - http://www.chiark.greenend.org.uk/~sgtatham/putty/download.html
- Run PuTTYgen
  - If SmartScreen blocks it:
    "More info" → "Run anyway"
  - "Load" → Choose your .pem file
    → Click "Save private key"
    → Save your .ppk file

- Run PuTTY
  - "SSH" → "Auth"
    →



    → Open your .ppk file
  - "Session"
    → Input your instance's Public IP to "Host Name" field
  - Click "Open"
    → Input ubuntu <Enter>



Ubuntu: AWS

- Create virtual memory space

```
$ sudo /bin/dd if=/dev/zero of=/var/swap.1 bs=1M count=1024
$ sudo /sbin/mkswap /var/swap.1
$ sudo /sbin/swapon /var/swap.1
```

- Follow Ubuntu: Native Installation
- Remove virtual memory space

```
$ sudo swapoff /var/swap.1
$ sudo rm /var/swap.1
```

- GUI settings
  - PuTTY: “Connection” → “SSH”
    → Check “Enable X11 forwarding”

```
$ sudo apt-get install python-tk tk-dev
$ pip uninstall -y matplotlib
$ pip install --user matplotlib
```

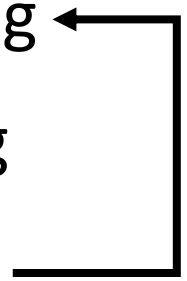
```
// Check whether GUI works properly
$ python
```

```
>>> import matplotlib.pyplot as plt
>>> plt.plot([1,2,3], [1,2,3])
>>> plt.show()
```

Getting Started: Image Classification

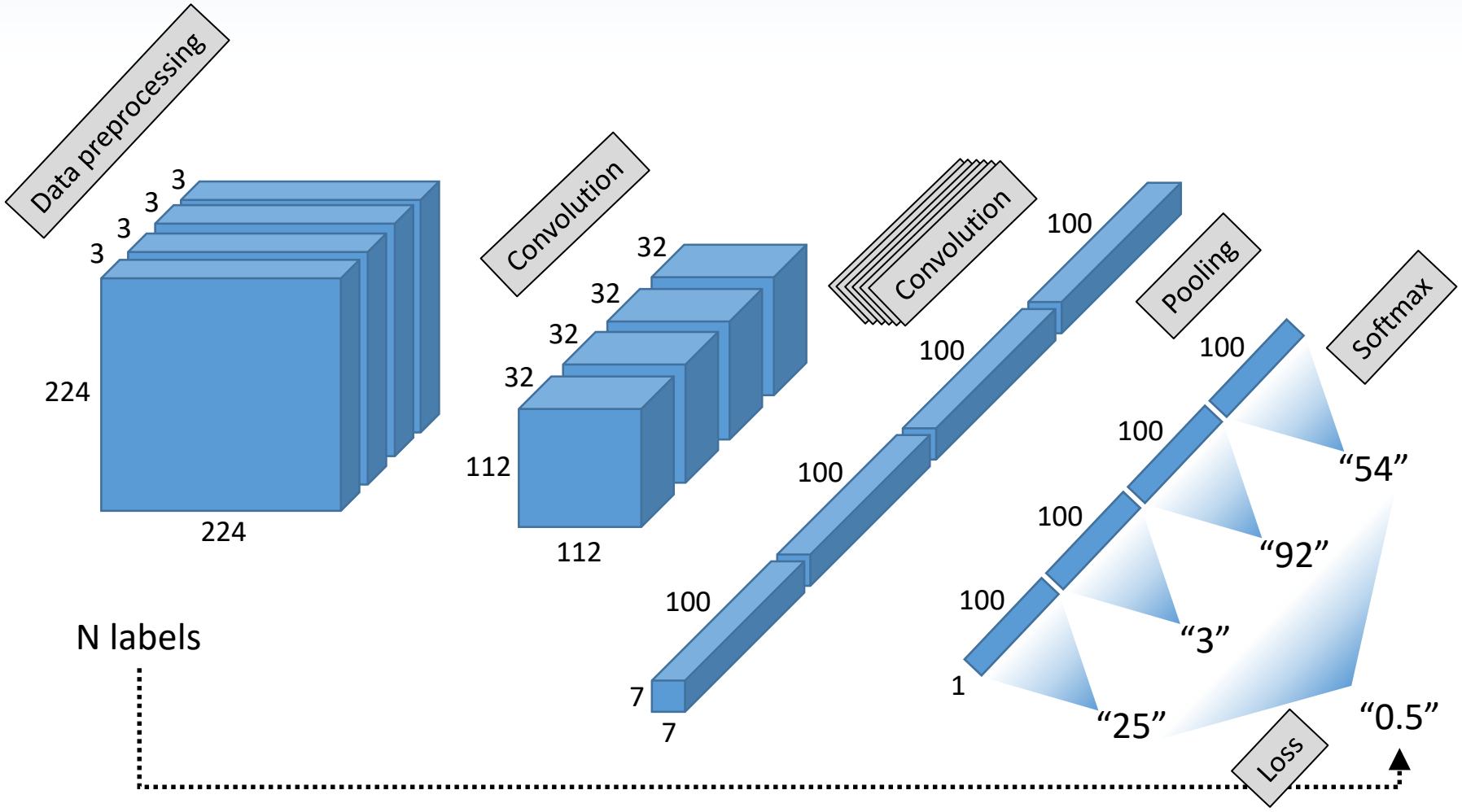
Common Workflow

- Network design
- Data preparation
- Training
- Testing
- Tuning



Network Design

N labeled images



N labels

Network Design

- Data layer
  - **source:** Input data path
  - **batch_size:** # of images per iteration
  - **crop_size:** Random (TRAIN) or Center (TEST)
  - **mirror:** Flip LR (50% random)
  - **mean_value:** Use 3 times (BGR-order)
  - **top:** first = data, second (optional) = label
- Pooling layer
  - **pool:** MAX, AVE, STOCHASTIC
  - **global_pooling:** 1 x 1 output
  - **kernel_size, pad, stride:** Normal pooling
- Loss layer
  - **type:** Loss function
  - SoftmaxWithLoss = Softmax → MultinomialLogisticLoss
  - **bottom:** first = prediction, second = label

```
layer {
  name: "data/data"
  type: "Data"
  top: "data"
  top: "label"
  data_param {
    source: "data/train_lmdb"  backend: LMDB  batch_size: 128
  }
  transform_param {
    crop_size: 224  mirror: true
    mean_value: 104  mean_value: 117  mean_value: 123
  }
  include { phase: TRAIN }
}
```

```
layer {
  name: "pool6/pool"
  type: "Pooling"
  bottom: "conv5"
  top: "pool6"
  pooling_param { pool: AVE  global_pooling: true }
}
```

```
layer {
  name: "loss"
  type: "SoftmaxWithLoss"
  bottom: "pool6"
  bottom: "label"
  top: "loss"
}
```

Network Design

- Convolution layer
  - **num_output:** # of output channels
  - **bias_term:** Whether use or not (default: true)
- ReLU layer
  - **negative_slope:** Nonzero slope for negative inputs (default: 0)
  - **bottom = top:** In-place operation
- Example
  - 5 “Conv → ReLU” layers
  - num_output: 32 → 64 → 128 → 256 → 100
  - kernel_size: 3, pad: 1, stride: 2
    ➔ Height, Width: 112 → 56 → 28 → 14 → 7

```
layer {
  name: "conv1/conv"
  type: "Convolution"
  bottom: "data"
  top: "conv1"
  convolution_param {
    num_output: 32
    kernel_size: 3  pad: 1  stride: 2
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv1/relu"
  type: "ReLU"
  bottom: "conv1"
  top: "conv1"
}
```

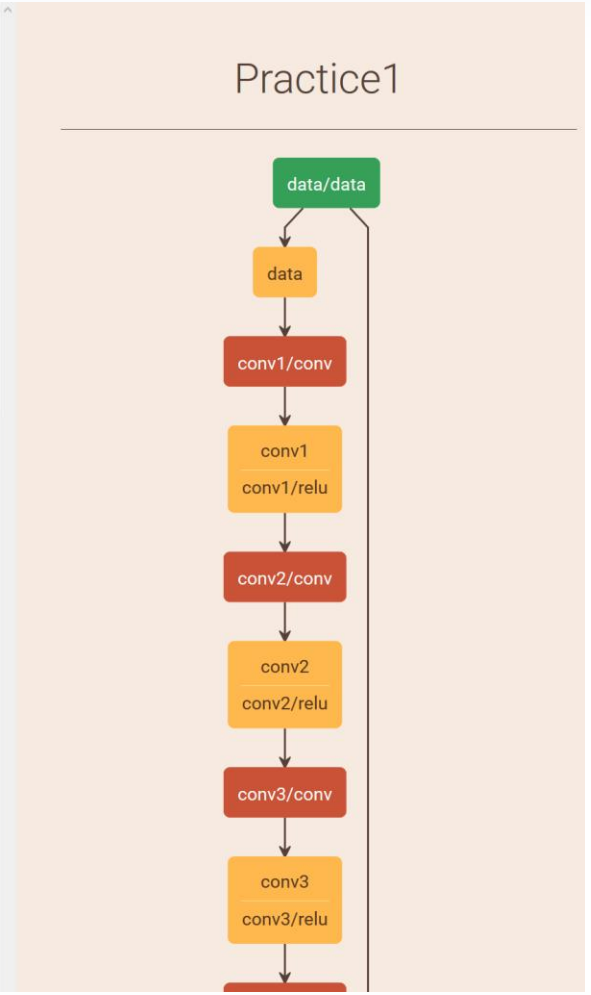
Network Design: Additional Information

- Convolution layer
  - **kernel_h, kernel_w, stride_h, stride_w, pad_h, pad_w:** 2D rectangular convolution
  - **group:** Convolution with channel-wise slicing (default: 1)
    - "num_output: 256, group: 4, input channel: 128" = 4 convolutions of "num_output: 256 / 4, input channel: 128 / 4"
  - **axis:** Channel axis index (default: 1)
    - "axis: 2, input: 64 x 32 x 28 x 28" = 1D convolution of "batch_size: 64 * 32, channel: 28, spatial size: 28"
    - "axis: 1, input: 64 x 32 x 28 x 28 x 28" = 3D convolution of "batch_size: 64, channel: 32, spatial size: 28 x 28 x 28"
- **Output shape difference: Convolution vs. Pooling**
  - Conv output size = floor((input_size + 2*pad - kernel_size) / stride) + 1
  - Pool output size = ceil((input_size + 2*pad - kernel_size) / stride) + 1
  - Not corrected yet due to backward compatibility (https://github.com/BVLC/caffe/issues/1318)
- Loss layer
  - **ignore_label:** Label index to be ignored (e.g., for hard example mining)
- Every layer
  - **loss_weight:** If > 0, corresponding top data is considered as a loss term (default: 0)

Network Design: Visualization

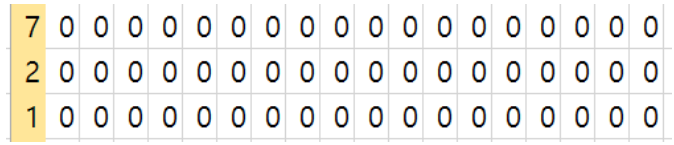
- Netscope
  - http://ethereon.github.io/netscope/#/editor
  - Paste your prototxt and “Shift + Enter”
  - Not displayed correctly in IE and Edge
- Examples: AlaxNet, GoogLeNet, VGG
  - http://ethereon.github.io/netscope/#/preset/alexnet
  - http://ethereon.github.io/netscope/#/preset/googlenet
  - http://ethereon.github.io/netscope/#/preset/vgg-16

```
name: "Practice1"
layer {
  name: "data/data"
  type: "Data"
  top: "data"
  top: "label"
  data_param {
    source: "data/train_lmdb"  backend: LMDB  batch_size: 128
  }
  transform_param {
    crop_size: 224  mirror: true
    mean_value: 104  mean_value: 117  mean_value: 123
  }
  include { phase: TRAIN }
}
layer {
  name: "conv1/conv"
  type: "Convolution"
  bottom: "data"
  top: "conv1"
  convolution_param {
    num_output: 32
    kernel_size: 3  pad: 1  stride: 2
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv1/relu"
  type: "ReLU"
  bottom: "conv1"
  top: "conv1"
}
layer {
  name: "conv2/conv"
  type: "Convolution"
  bottom: "conv1"
  top: "conv2"
  convolution_param {
    num_output: 64
    kernel_size: 3  pad: 1  stride: 2
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv2/relu"
  type: "ReLU"
```



Data Preparation

- We have datasets in the form of…
  - Numerical vectors: .txt, .csv, .xls, .mat, .pkl, …
  - Images: <root>/<class>/<filename>
    - train/person/000001.jpg, test/n101024/000123.jpg, …
  - Documents: plain text, XML, ...
  - …



- To use datasets in Caffe
  - Option 1: Convert datasets to LMDB or LevelDB → Use Data layer
  - Option 2: Implement your Python data layer

Data Preparation: LMDB?

- Key-value DB (dictionary or hash)
  - Key = byte array, Value = byte array (i.e., arbitrary data type & size for each record)
- Support multi-threaded environments
  - Read performance scales linearly with # of readers
  - One writer at a time
  - Transaction does not block other transactions (e.g., writer doesn’t block readers)
- Ultra-fast
  - No transaction log, appending mode, …
  - “Unmatched” in-memory performance & Outstanding on-disk performance

Data Preparation: Images → LMDB

- ImageNet DB

```
~/caffe# mkdir data/imagenet
```

```
$ cd <your ImageNet download location>
$ sudo docker cp val.txt caffe:/root/caffe/data/imagenet
$ sudo docker cp val caffe:/root/caffe/data/imagenet
```

- Tiny DB

```
~/caffe# ln -s /root/caffe/caffe-materials/tiny_lmdb data/tiny_lmdb
```

Data Preparation: Images → LMDB

- Using convert_imageset
  -
```
$ <Caffe root>/build/tools/convert_imageset -encoded=true -encode_type="jpg"
                                            -resize_height=256 -resize_width=256
                                            -shuffle=true
                                            data/images/
```
  - .txt file: List of <fi

```
train/ILSVRC2012_val_000
train/ILSVRC2012_val_000
train/ILSVRC2012_val_000
train/ILSVRC2012_val_000
train/ILSVRC2012_val_000
...
```

```
~/caffe# ./build/tools/convert_imageset \
                    -encoded=true -encode_type="jpg" \
                    -resize_height=256 -resize_width=256 \
                    data/imagenet/ \
                    data/imagenet/val.txt \
                    data/imagenet/train_lmdb
```

```
~/caffe# cp -r data/imagenet/train_lmdb data/imagenet/test_lmdb
```

```
    source: data/train_lmdb  backend: LMDB  batch_size: 128
    crop_size: 224  mirror: true
    mean_value: 104  mean_value: 117  mean_value: 123
  }
  include { phase: TRAIN }
}
```

Training

```
~/caffe# ./build/tools/caffe train -solver caffe-materials/practice1/solver.pt

GPU mode:
~/caffe# ./build/tools/caffe train -gpu 0 \
                    -solver caffe-materials/practice1/solver-gpu.pt
```

- Stochastic optimization for $t = 1, 2, \dots, T$
  - Sampling mini-batch data: $X_t = [x_1, x_2, \dots, x_M]$
  - Forward-pass
    - Output $[f(x_1), f(x_2), \dots, f(x_M)]$ and Loss $\sum_{i=1}^{M} l(y_i, f(x_i))$
  - Backward-pass: Gradient $\frac{\partial E}{\partial w}$
  - Update: $w \leftarrow w - \eta_t h_t \left(\frac{\partial E}{\partial w}\right)$
- Prototxt
  - Number of iterations T, Learning rate η_t, Solver $h_t(\dots)$
  - **iter_size:** Update with multiple mini-batches
- Run
  - `$ ./build/tools/caffe train -solver solver.pt -gpu 0`

```
net: "practice1.pt"

max_iter: 300000
iter_size: 2

lr_policy: "step"
base_lr: 0.003
gamma: 0.3165
stepsize: 60000

type: "SGD"
momentum: 0.9
weight_decay: 0.0002
solver_mode: CPU

display: 20
snapshot: 20000
snapshot_prefix: "practice1_train"
```

Cafe

Testing

- Network prototxt
  - include { phase: TEST }
  - Data layer
    - **source:** Test DB path
  - Accuracy layer
    - **top_k:** Top-k accuracy
- Solver prototxt
  - For testing during training
    - **test_interval:** Interval of testing
    - **test_iter:** # of iterations

```
17 layer {
18   name: "data/data"
19   type: "Data"
20   top: "data"
21   top: "label"
22   data_param {
23     source: "data/test_lmdb"  backend: LMDB  batch_size: 128
24   }
25   transform_param {
26     crop_size: 224  mirror: true
27     mean_value: 104  mean_value: 117  mean_value: 123
28   }
29   include { phase: TEST }
30 }
```

```
132 layer {
133   name: "accuracy"
134   type: "Accuracy"
135   bottom: "pool6"
136   bottom: "label"
137   top: "accuracy"
138   include { phase: TEST }
139 }
140 layer {
141   name: "accuracy_top5"
142   type: "Accuracy"
143   bottom: "pool6"
144   bottom: "label"
145   top: "accuracy_top5"
146   accuracy_param { top_k: 5 }
147   include { phase: TEST }
148 }
```

```
1  net: "practice1.pt"
2
3  max_iter: 300000
4  iter_size: 2
5
6  lr_policy: "step"
7  base_lr: 0.003
8  gamma: 0.3165
9  stepsize: 60000
10
11 type: "SGD"
12 momentum: 0.9
13 weight_decay: 0.0002
14 solver_mode: CPU
15
16 display: 20
17 snapshot: 20000
18 snapshot_prefix: "practice1_train"
19
20 test_interval: 20000
21 test_iter: 500
```

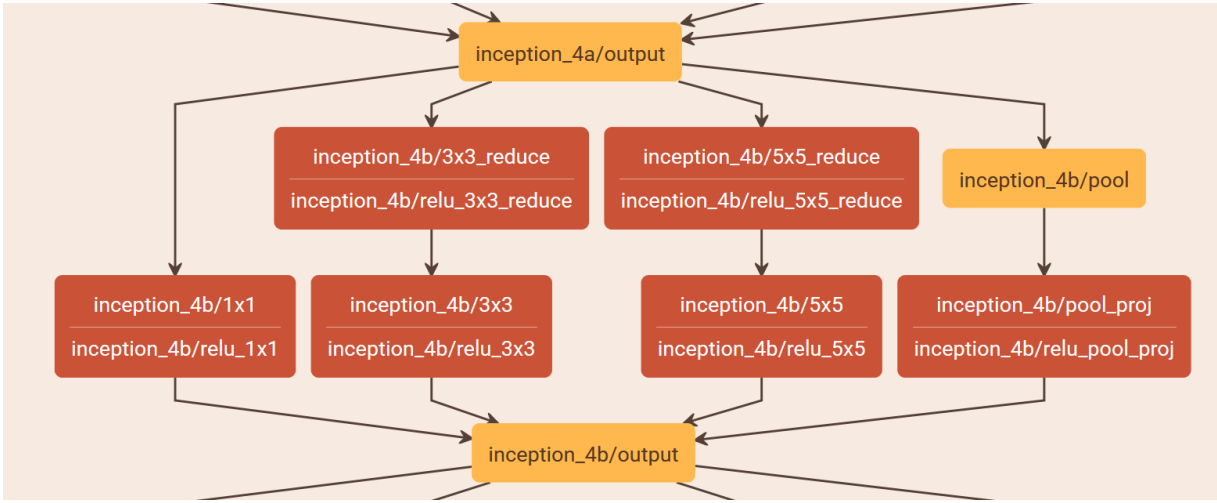
Testing

```
~/caffe# ./build/tools/caffe test \
   -model caffe-materials/practice2/train_val.prototxt \
   -weights caffe-materials/practice2/squeezenet_v1.1.caffemodel \
   -gpu 0
```

- Testing
  - ```
    $ ./build/tools/caffe test -model net.pt
                               -weights net_train_iter_300000.caffemodel
                               -gpu 0
                               -iterations 100
    ```
- Profiling
  - ```
    $ ./build/tools/caffe time -model net.pt
                               -gpu 0
                               -iterations 100
                               -phase TEST
    ```

Tuning

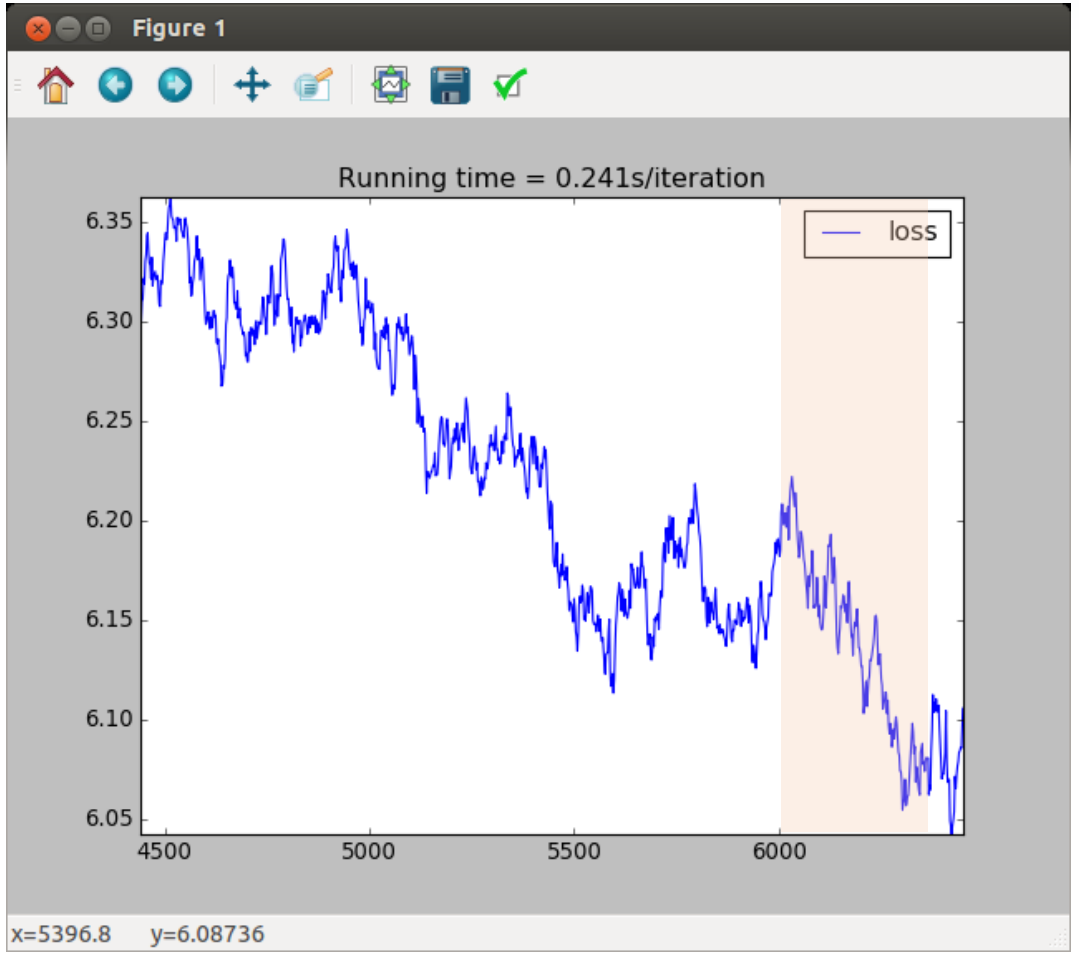
- Parameter tuning
  - Solver prototxt: base_lr
  - Network prototxt: num_output
- Network re-design
  - Advanced building blocks
  - Batch normalization, C.ReLU, Squeezing, Inception, Residual, Multi-scale feature, …



More Examples

Training: Visualization?

```
I0731 17:16:06.876653  4320 solver.cpp:228] Iteration 6000, loss = 5.93425
I0731 17:16:11.765796  4320 solver.cpp:228] Iteration 6020, loss = 6.05768
I0731 17:16:16.568244  4320 solver.cpp:228] Iteration 6040, loss = 6.39608
I0731 17:16:21.438531  4320 solver.cpp:228] Iteration 6060, loss = 6.13255
I0731 17:16:26.282059  4320 solver.cpp:228] Iteration 6080, loss = 6.26793
I0731 17:16:31.161669  4320 solver.cpp:228] Iteration 6100, loss = 5.92059
I0731 17:16:36.031781  4320 solver.cpp:228] Iteration 6120, loss = 6.50278
I0731 17:16:40.830622  4320 solver.cpp:228] Iteration 6140, loss = 5.9315
I0731 17:16:45.686990  4320 solver.cpp:228] Iteration 6160, loss = 6.05751
I0731 17:16:50.473193  4320 solver.cpp:228] Iteration 6180, loss = 5.98048
I0731 17:16:55.304819  4320 solver.cpp:228] Iteration 6200, loss = 5.85572
I0731 17:17:00.104171  4320 solver.cpp:228] Iteration 6220, loss = 6.05796
I0731 17:17:04.934598  4320 solver.cpp:228] Iteration 6240, loss = 5.90128
I0731 17:17:09.769328  4320 solver.cpp:228] Iteration 6260, loss = 6.09975
I0731 17:17:14.618911  4320 solver.cpp:228] Iteration 6280, loss = 6.33493
I0731 17:17:19.412217  4320 solver.cpp:228] Iteration 6300, loss = 5.84982
I0731 17:17:24.235080  4320 solver.cpp:228] Iteration 6320, loss = 6.39197
I0731 17:17:29.127218  4320 solver.cpp:228] Iteration 6340, loss = 5.85397
I0731 17:17:33.995726  4320 solver.cpp:228] Iteration 6360, loss = 6.19559
I0731 17:17:38.840620  4320 solver.cpp:228] Iteration 6380, loss = 6.21344
I0731 17:17:43.661043  4320 solver.cpp:228] Iteration 6400, loss = 6.22203
```



Training with Python

- Python interface
  - Load, Save, Train, Test
  - Access trainable parameters & intermediate data
- For more information
  - python/caffe/_caffe.cpp: BOOST_PYTHON_MODULE(_caffe) { ... }

```
~/caffe# python caffe-materials/practice3/py_train_1.py
```

```python
import caffe

# Use GPU 0
caffe.set_mode_gpu()
caffe.set_device(0)

# Initialize solver
solver = caffe.SGDSolver('solver.pt')

# Restore snapshot
solver.restore('net_train_iter_300000.solverstate')
# or trained parameters
solver.net.copy_from('net_train_iter_300000.caffemodel')

# Train 10 iterations
solver.step(10)

# Access 'pool6' data (NumPy array)
pool6_data = solver.net.blobs['pool6'].data
print pool6_data.shape   # (32, 1000, 1, 1)

# Save snapshot
solver.snapshot()
```

Training with Python: Visualization

```
~/caffe# python caffe-materials/practice3/py_train_2.py
```

- Initialization

```
import caffe
import matplotlib.pyplot
import time as timelib

solver = caffe.SGDSolver('solver.pt')

fig, axes = matplotlib.pyplot.subplots()
fig.show()

loss_list = []
max_iter = 10000
iter0 = solver.iter
```

- Training & Drawing

```
while solver.iter < max_iter:
  solver.step(1)

  loss = solver.net.blobs['loss'].data.flatten()
  loss_list.append(loss)

  # Update plot for every 500 iterations
  if solver.iter % 500 == 0:
    axes.clear()
    axes.plot(range(iter0, iter0+len(loss_list)), loss_list)
    axes.grid(True)
    fig.canvas.draw()
    matplotlib.pyplot.pause(0.01)

solver.snapshot()
fig.savefig('fig_iter_%d.png' % solver.iter)
```

Training with Python: Advanced Scheduling

- Caffe LR policy
  - η_t = base_lr * $\eta(t)$
  - Manipulating base_lr in Python causes no conflict with any Caffe LR policy
- Advanced scheduling
  - If loss plateaus, reduce base_lr
  - If base_lr is too small, restore it
  - Problem: No Python interface to access base_lr

```
template <typename Dtype>
Dtype SGDSolver<Dtype>::GetLearningRate() {
  Dtype rate;
  const string& lr_policy = this->param_.lr_policy();

  if (lr_policy == "fixed") {
    rate = this->param_.base_lr();
  }
  else if (lr_policy == "step") {
    this->current_step_ = this->iter_ / this->param_.stepsize();
    rate = this->param_.base_lr() *
        pow(this->param_.gamma(), this->current_step_);
  }
  else if (lr_policy == "exp") {
    rate = this->param_.base_lr() *
        pow(this->param_.gamma(), this->iter_);
  }
  ...
  return rate;
}
```

Training with Python: Advanced Scheduling

- Add functions to get & set base_lr
  - include/caffe/solver.hpp

```
template <typename Dtype>
class Solver {
 public:
  ...
  Dtype GetBaseLearningRate() { return param_.base_lr(); }
  void SetBaseLearningRate(const Dtype base_lr);
  ...
```

  - src/caffe/solver.cpp

```
namespace caffe {
...
template <typename Dtype>
void Solver<Dtype>::SetBaseLearningRate(const Dtype base_lr) {
  param_.set_base_lr(base_lr);
}
...
```

- Add Python interface
  - python/caffe/_caffe.cpp

```
...
.def("step", &Solver<Dtype>::Step)
.def("get_base_lr", &Solver<Dtype>::GetBaseLearningRate)
.def("set_base_lr", &Solver<Dtype>::SetBaseLearningRate)
.def("restore", &Solver<Dtype>::Restore)
.def("snapshot", &Solver<Dtype>::Snapshot);
...
```

- Make

```
$ make -j$(nproc) && make pycaffe
```

Training with Python: Advanced Scheduling

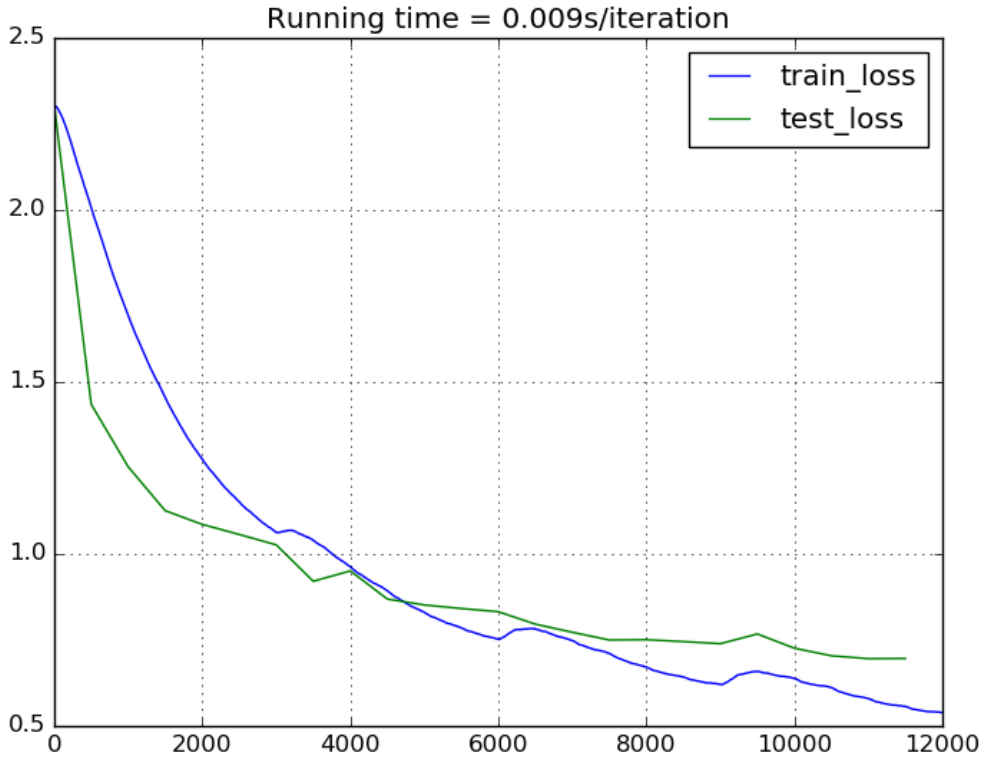
- Moving average of loss

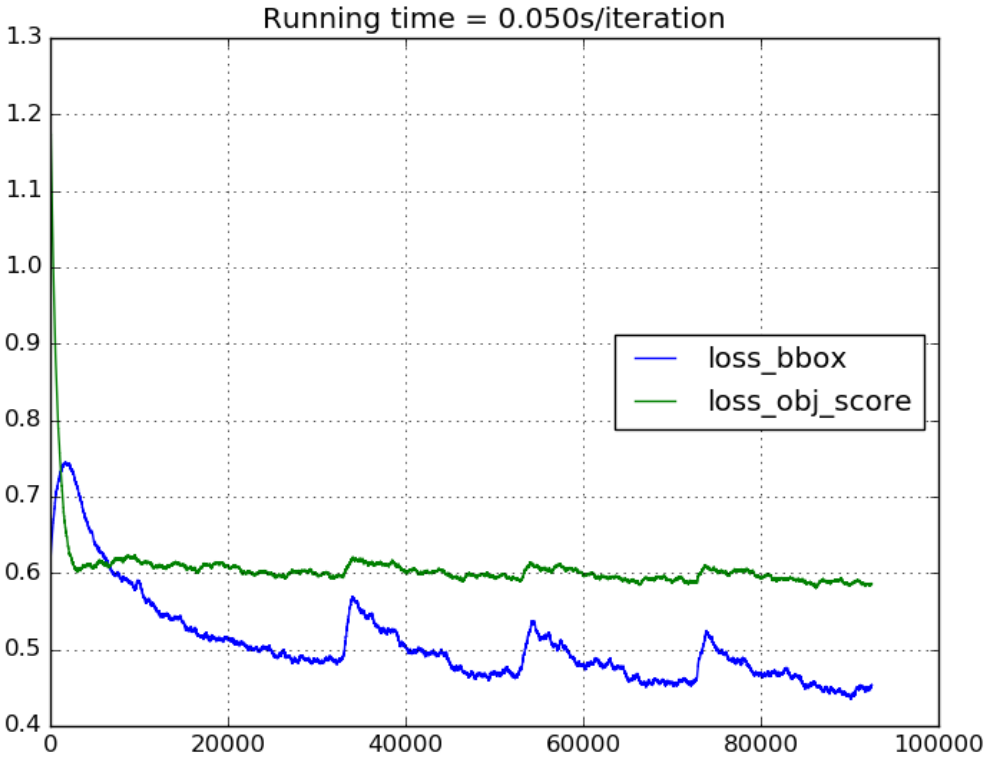
```
while solver.iter < max_iter:
  solver.step(1)
  loss = solver.net.blobs['loss'].data.flatten()

  if len(loss_list) == 0:
    mean_loss = loss
  else:
    mean_loss = 0.999 * mean_loss + 0.001 * loss
  loss_list.append(mean_loss)
```

- LR policy: Plateau + Multi-round

```
window = [0, 1000]
base_lr0 = solver.get_base_lr()

while solver.iter < max_iter:
  solver.step(1)
  ...
  loss_list.append(mean_loss)

  if len(loss_list) - window[0] > window[1] and \
       mean_loss > 0.99 * loss_list[-window[1]]:
    solver.set_base_lr(solver.get_base_lr() * 0.5)
    window[0] = len(loss_list)
    window[1] *= 2

  if solver.get_base_lr() < 0.1 * base_lr0:
    solver.set_base_lr(base_lr0)
    window[1] = 1000
```

Training with Python: Advanced Scheduling






```
~/caffe# python caffe-materials/practice3/py_train_4.py
```

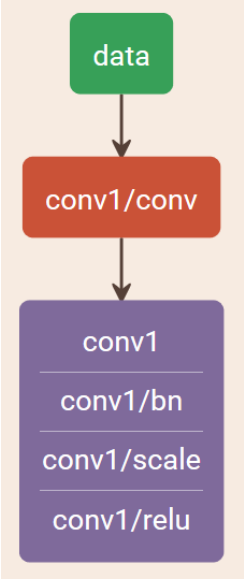
Advanced Building Blocks

- Batch Normalization
  - Faster and more stable convergence
  - S. Ioffe & C. Szegedy (2015), ICML-2015, https://arxiv.org/abs/1502.03167
- Concatenated ReLU
  - 2x faster computation in early stages of CNNs
  - W. Shang, K. Sohn, D. Almeida & H. Lee (2016), ICML-2016, https://arxiv.org/abs/1603.05201
- Residual Connections
  - Very deep networks converge much better
  - K. He, X. Zhang, S. Ren & J. Sun (2016), CVPR-2016, https://arxiv.org/abs/1512.03385

Batch Normalization

- Convolution $y = Wx + b$
  - bias_term: false
- BatchNorm $y \leftarrow \frac{y - mean(y)}{std(y)}$
  - 3 internal parameters
  - Do **not** specify use_global_stats
- Scale $y \leftarrow \alpha y + \beta$
  - bias_term: true
- ReLU $y \leftarrow g(y)$

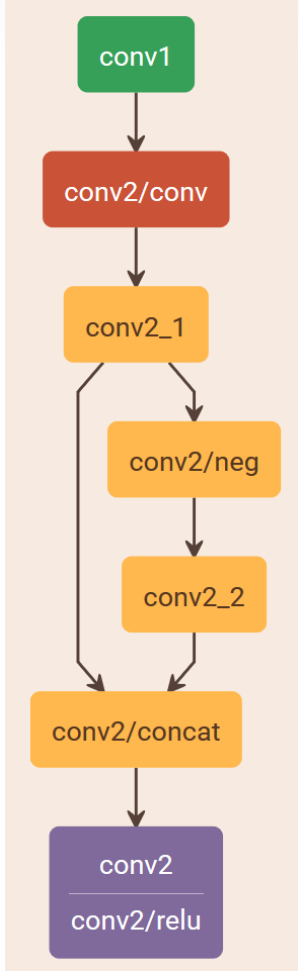
```
layer {
  name: "conv1/conv"
  type: "Convolution"
  bottom: "data"
  top: "conv1"
  #param { name: "conv1/conv/weight"  lr_mult: 1  decay_mult: 1 }
  convolution_param {
    num_output: 64  kernel_size: 3  stride: 1  pad: 1
    bias_term: false
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv1/bn"
  type: "BatchNorm"
  bottom: "conv1"
  top: "conv1"
  #batch_norm_param { use_global_stats: false }
  #param { name: "conv1/bn/mean"  lr_mult: 0  decay_mult: 0 }
  #param { name: "conv1/bn/var"  lr_mult: 0  decay_mult: 0 }
  #param { name: "conv1/bn/count"  lr_mult: 0  decay_mult: 0 }
}
layer {
  name: "conv1/scale"
  type: "Scale"
  bottom: "conv1"
  top: "conv1"
  param { name: "conv1/scale/weight"  lr_mult: 1  decay_mult: 1 }
  param { name: "conv1/scale/bias"  lr_mult: 2  decay_mult: 0 }
  scale_param { bias_term: true }
}
layer {
  name: "conv1/relu"
  type: "ReLU"
  bottom: "conv1"
  top: "conv1"
}
```



Concatenated ReLU

- Convolution $y_1 = Wx + b$
  - num_output: / 2
- Power (negation) $y_2 = -y_1$
  - scale: -1
  - shift: 0, power: 1 (default)
- Concat $y = [y_1; y_2]$
  - axis: 1 (= channel-wise, default)
- ReLU $y \leftarrow g(y)$

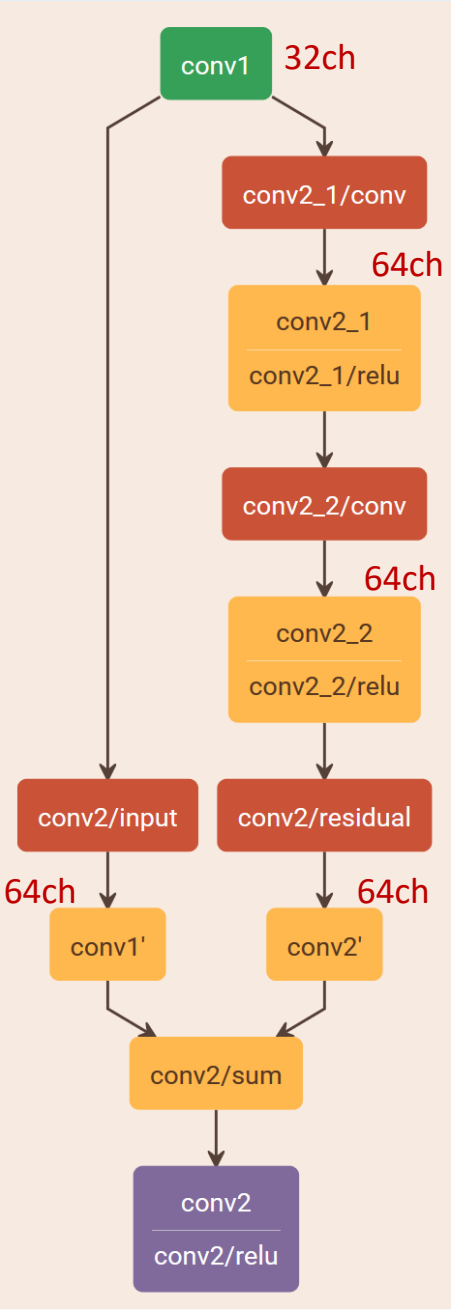
```
layer {
  name: "conv2/conv"
  type: "Convolution"
  bottom: "conv1"
  top: "conv2_1"
  convolution_param {
    num_output: 32  kernel_size: 3  pad: 1  stride: 2
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv2/neg"
  type: "Power"
  bottom: "conv2_1"
  top: "conv2_2"
  power_param {
    scale: -1.0
    #shift: 0.0  power: 1.0
  }
}
layer {
  name: "conv2/concat"
  type: "Concat"
  bottom: "conv2_1"
  bottom: "conv2_2"
  top: "conv2"
  #concat_param { axis: 1 }
}
layer {
  name: "conv2/relu"
  type: "ReLU"
  bottom: "conv2"
  top: "conv2"
}
```



Residual Connections

- Convolution $\boldsymbol{y}' = \boldsymbol{W}_r f(\boldsymbol{x}) + \boldsymbol{b}_r$
  - $f(\boldsymbol{x})$: Any multi-layer func.
  - Do **not** use ReLU for final output
- Convolution $\boldsymbol{x}' = \boldsymbol{W}_p \boldsymbol{x} + \boldsymbol{b}_p$
  - Use **only** for shape matching
- Eltwise $\boldsymbol{y} = \boldsymbol{x}' + \boldsymbol{y}'$
- ReLU $\boldsymbol{y} \leftarrow g(\boldsymbol{y})$

```
layer {
  name: "conv2/residual"
  type: "Convolution"
  bottom: "conv2_2"
  top: "conv2'"
  convolution_param {
    num_output: 64  kernel_size: 3  pad: 1  stride: 1
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv2/input"
  type: "Convolution"
  bottom: "conv1"
  top: "conv1'"
  convolution_param {
    num_output: 64  kernel_size: 1  pad: 0  stride: 1
    weight_filler { type: "xavier" }
  }
}
layer {
  name: "conv2/sum"
  type: "Eltwise"
  bottom: "conv1'"
  bottom: "conv2'"
  top: "conv2"
  eltwise_param { operation: SUM  coeff: 1  coeff: 1 }
}
layer {
  name: "conv2/relu"
  type: "ReLU"
  bottom: "conv2"
  top: "conv2"
}
```



Network Construction with Python

- Writing prototxt for repeating patterns is very annoying and easy to make mistakes
- Caffe provides an interface for programmable network prototxt generation
- See src/caffe/proto/caffe.proto for more information
  - NetParameter: Network prototxt
  - LayerParameter: layer { ... }
  - ParamSpec: param { ... }
  - XXXParameter: XXX_param { ... }

Network Construction with Python

```
>>> import caffe
>>> layer = caffe.proto.caffe_pb2.LayerParameter()
>>> dir(layer)
['name', 'type', 'bottom', 'top', 'param',
 'accuracy_param', ..., 'window_data_param',
 'include', 'loss_weight', 'propagate_down', ...]

>>> layer.name = 'some_layer'
>>> layer.type = 'SomeType'
>>> layer.bottom.append('input1')
>>> layer.bottom.append('input2')
>>> layer.top.append('output1')
>>> layer.top.append('output2')
>>> layer  # equals to 'print str(layer)'
name: "some_layer"
type: "SomeType"
bottom: "input1"
bottom: "input2"
top: "output1"
top: "output2"
```

```
>>> net = caffe.proto.caffe_pb2.NetParameter()
>>> dir(net)
[..., 'MergeFromString', 'ParseFromString',
 'SerializeToString', 'layer', ...]

>>> net.layer.extend([layer])
>>> net  # equals to 'print str(net)'
layer {
  name: "some_layer"
  type: "SomeType"
  bottom: "input1"
  bottom: "input2"
  top: "output1"
  top: "output2"
}
```

```
>>> net.layer.extend([layer])
>>> net
layer {
  name: "some_layer"
  ...
}
layer {
  name: "some_layer"
  ...
}
```

Network Construction with Python

- caffe_pb2?

```
message LayerParameter {
  optional string name = 1;
  optional string type = 2;
  repeated string bottom = 3;
  repeated string top = 4;

  optional Phase phase = 10;

  repeated float loss_weight = 5;

  repeated ParamSpec param = 6;
  ...
```

src/caffe/proto/caffe.proto


```
class LayerParameter : public ::google::protobuf::Message {
  ...
  // optional string name = 1;
  bool has_name() const;
  void clear_name();
  static const int kNameFieldNumber = 1;
  const ::std::string& name() const;
  void set_name(const ::std::string& value);
  ...

  // optional string type = 2;
  ...

  // repeated string bottom = 3;
  int bottom_size() const;
  void clear_bottom();
  static const int kBottomFieldNumber = 3;
  const ::std::string& bottom(int index) const;
  ::std::string* mutable_bottom(int index);
  void set_bottom(int index, const ::std::string& value);
  void set_bottom(int index, const char* value);
  void set_bottom(int index, const char* value, size_t size);
  ::std::string* add_bottom();
  void add_bottom(const ::std::string& value);
  ...

  // repeated string top = 4;
  ...
```

build/src/caffe/proto/caffe.pb.cc
python/caffe/proto/caffe.pb2.py

build/src/caffe/proto/caffe.pb.h

Network Construction with Python

- Network instance can be initialized from (ParseFromString) or merged with (MergeFromString) other network instance

```
>>> net.MergeFromString(net.SerializeToString())
>>> net
layer {
  name: "some_layer"
  ...
}
layer {
  name: "some_layer"
  ...
}
layer {
  name: "some_layer"
  ...
}
layer {
  name: "some_layer"
  ...
}
```

Network Construction with Python

```
def base_layer(layer_name, type_name, \
               bottom_names, top_names):
  layer = caffe.proto.caffe_pb2.LayerParameter()
  layer.name = layer_name
  layer.type = type_name
  layer.bottom.extend(bottom_names)
  layer.top.extend(top_names)
  return layer
```

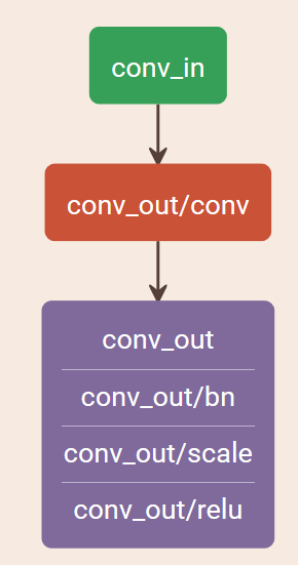
```
def convolution_layer(bottom_name, top_name, \
      num_output, kernel_size, stride=1, pad=0, \
      group=1, bias_term=True):
  layer_name = top_name + '/conv'
  layer = base_layer(layer_name, 'Convolution', \
                     [bottom_name], [top_name])
  layer.convolution_param.num_output = num_output
  layer.convolution_param.kernel_size.append(kernel_size)
  layer.convolution_param.stride.append(stride)
  layer.convolution_param.pad.append(pad)
  layer.convolution_param.group = group
  layer.convolution_param.bias_term = bias_term
  layer.convolution_param.weight_filler.type = 'xavier'
  return layer
```

```
>>> convolution_layer('conv_in', 'conv_out', 32, 3)
name: "conv_out/conv"
type: "Convolution"
bottom: "conv_in"
top: "conv_out"
convolution_param {
  num_output: 32
  bias_term: true
  pad: 0
  kernel_size: 3
  group: 1
  stride: 1
  weight_filler {
    type: "xavier"
  }
}
```

Network Construction with Python

```
def conv_module(bottom_name, top_name, \
                num_output, kernel_size, \
                stride=1, pad=0, group=1):
  module = caffe.proto.caffe_pb2.NetParameter()
  # Conv layer
  module.layer.extend( \
    [convolution_layer(bottom_name, top_name, \
          num_output, kernel_size, stride, pad, \
          group, bias_term=False)])
  # BatchNorm layer
  module.layer.extend( \
    [batch_norm_layer(top_name, top_name)])
  # Scale layer
  module.layer.extend( \
    [scale_layer(top_name, top_name, bias_term=True)])
  # ReLU layer
  module.layer.extend( \
    [relu_layer(top_name, top_name)])
  return module
```

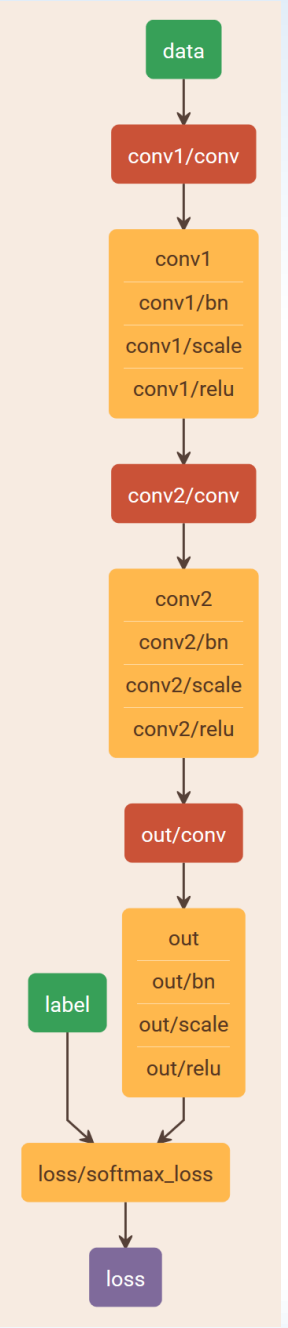
```
>>> conv_module('conv_in', 'conv_out', 32, 3)
layer {
  name: "conv_out/conv"
  type: "Convolution"
  bottom: "conv_in"
  top: "conv_out"
  convolution_param {
    num_output: 32
    ...
    weight_filler {
      type: "xavier"
    }
  }
}
layer {
  name: "conv_out/bn"
  type: "BatchNorm"
  bottom: "conv_out"
  top: "conv_out"
}
layer {
  name: "conv_out/scale"
  type: "Scale"
  bottom: "conv_out"
  top: "conv_out"
  scale_param {
    bias_term: true
  }
}
layer {
  name: "conv_out/relu"
  type: "ReLU"
  bottom: "conv_out"
  top: "conv_out"
}
```



Network Construction with Python

```
def conv_net(names, channels, kernels, strides):
  net = caffe.proto.caffe_pb2.NetParameter()
  # Data layer
  net.layer.extend( \
    [data_layer('data/train_lmdb', batch_size=64)])
  # Conv modules
  for i in range(len(channels)):
    pad = (kernels[i] - 1) / 2
    net.MergeFromString( \
      conv_module(names[i], names[i+1], \
                  channels[i], kernels[i], strides[i], pad) \
      .SerializeToString())
  # Loss layer
  net.layer.extend( \
    [softmax_loss_layer(['out', 'label'], 'loss')])
  return net
```

```
conv_net( \
  ['data', 'conv1', 'conv2', 'out'], \
  [32, 64, 10], \
  [3, 3, 3], \
  [2, 2, 2])
```



LMDB Access

- convert_imageset is only useful for image classification tasks, not widely applicable to various databases
- Any type of data can be stored as LMDB
  - LMDB stores data as a byte array
  - Need to implement encoder (data → bytes) and decoder (bytes → data)

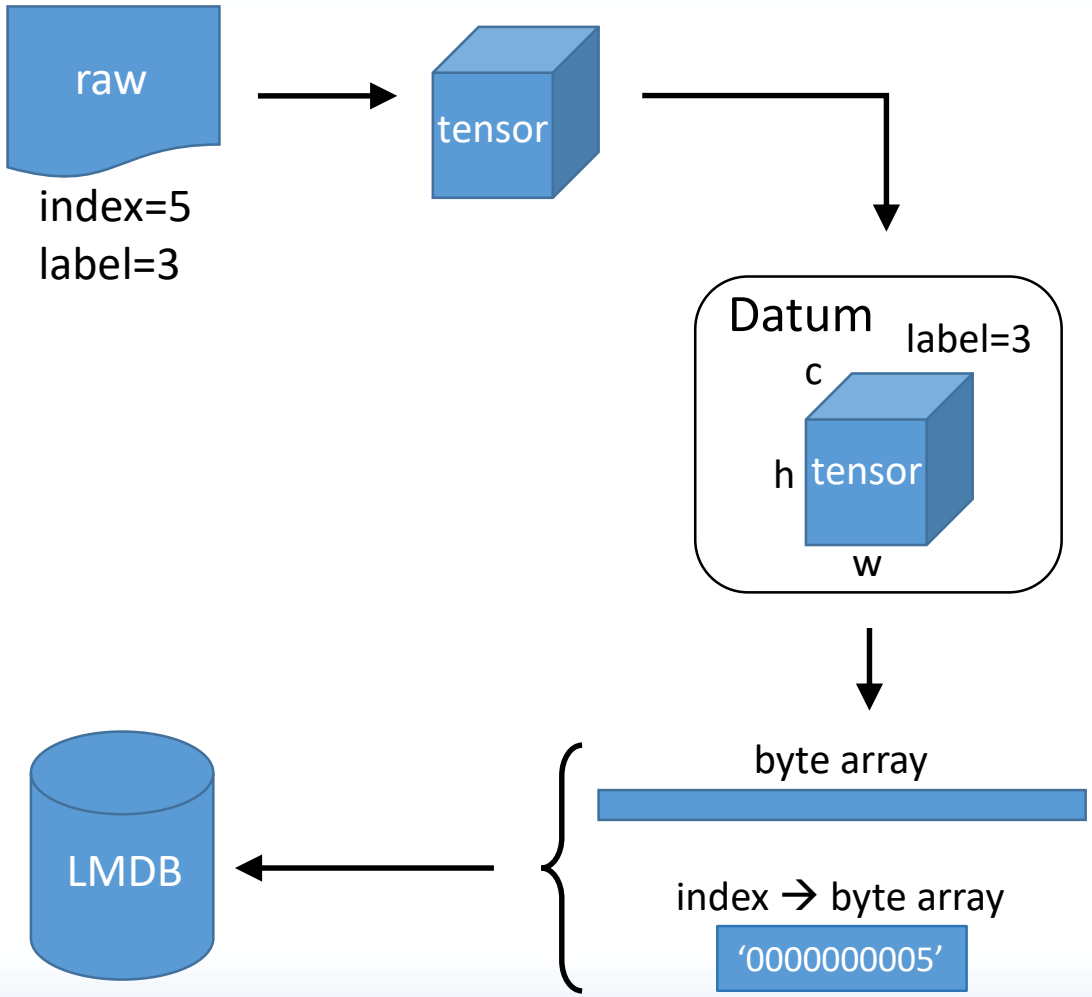
- Also related with src/caffe/proto/caffe.proto
- **Datum**: Data point instance
  - bytes data: Byte array of data
    - Can be an arbitrary type with a pre-processor
  - float float_data: Float array
    - Convenient to deal with real-valued vectors
  - int label: Label for classification tasks
  - int channels, height, width: Data shape
  - bool encoded: Whether data is an encoded image

LMDB Access: Python API Usage

```
>>> import lmdb
>>> reader = lmdb.open('data/imagenet/train_lmdb', readonly=True).begin()
>>> cursor = reader.cursor()
>>> cursor.next()
True
>>> cursor.key()
'00000000_train/n03476684/n03476684_14201.JPEG'
>>> cursor.value()
'"\x89\xdf\x02\xff\xd8\xff...\x01'
>>> cursor.next()
True
>>> cursor.key()
'00000001_train/n03642806/n03642806_6609.JPEG'
...
>>> cursor.close()
>>> cursor.key()
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
lmdb.Error: Attempt to operate on closed/deleted/dropped object.
```

LMDB Access: Storing Data

- For each data instance, do:
  1. Convert raw data → tensor
  2. Determine tensor's shape
  3. (Optional) Compress tensor
  4. Fill in Datum instance's fields
     (data, channels, width, height, label)
  5. Encode Datum → byte array
  6. Store { instance's index, byte array }
     to LMDB



LMDB Access: Storing Data

- For each data instance, do:
  1. Convert raw data → tensor
  2. Determine tensor's shape
  3. (Optional) Compress tensor
  4. Fill in Datum instance's fields (data, channels, width, height)
  5. Encode Datum → byte array
  6. Store { index, byte array } to LMDB

```
def write_lmdb(db_path, list_filename, height, width):
  map_size = 9999999999
  db = lmdb.open(db_path, map_size=map_size)
  writer = db.begin(write=True)
  datum = caffe.proto.caffe_pb2.Datum()
  for index, line in enumerate(open(list_filename, 'r')):
    img_filename, label = line.strip().split(' ')
    img = cv2.imread(img_filename, 1)
    img = cv2.resize(img, (height, width))
    _, img_jpg = cv2.imencode('.jpg', img)
    datum.channels = 3
    datum.height = height
    datum.width = width
    datum.label = int(label)
    datum.encoded = True
    datum.data = img_jpg.tostring()
    datum_byte = datum.SerializeToString()
    index_byte = '%010d' % index
    writer.put(index_byte, datum_byte, append=True)
  writer.commit()
  db.close()
```

LMDB open

1

2

3

4

5

6

Finalize & Close

LMDB Access: Loading Data

- For each data instance, do: (reverse order)
  1. Load { index, byte array } from LMDB
  2. Decode byte array → Datum
  3. Get required fields from Datum (data, label, ...)
  4. (Optional) Decompress tensor
  5. Determine tensor's shape
  6. Convert tensor → input data

```
import lmdb, cv2, caffe
import numpy as np

def read_lmdb(db_path):
  db = lmdb.open(db_path, readonly=True)
  reader = db.begin()
  cursor = reader.cursor()
  datum = caffe.proto.caffe_pb2.Datum()
  for index_byte, datum_byte in cursor:
    datum.ParseFromString(datum_byte)
    np_array = np.fromstring(datum.data, dtype=np.uint8)
    label = datum.label
    img = cv2.imdecode(np_array, 1)
    data = np.rollaxis(img, 2, 0)
    yield (data, label)
  cursor.close()
  db.close()
```

LMDB Access: Practice

- Storing data

```
~/caffe# python caffe-materials/practice5/lmdb_access.py write \
    caffe-materials/practice5/imagenet_small.txt \
    256 256 \
    data/imagenet/small_lmdb
```

- Loading data

```
~/caffe# python caffe-materials/practice5/lmdb_access.py read \
    data/imagenet/small_lmdb
```

LMDB Access: Some Tips

- Handling pairwise data: (x_n, y_n)
  - e.g., face recognition tasks, multivariate label, ...
  - Make 2 LMDBs: $\{x_1, x_2, x_3, \ldots, x_N\}$ and $\{y_1, y_2, y_3, \ldots, y_N\}$
  - Construct network with 2 data layer: data_x ($= x_n$) and data_y ($= y_n$)
  - Of course, never shuffle two LMDBs separately

Network Data Access

- We can do runtime access to network data in Python
  - Intermediate layer data

```
net.blobs['conv1'].data
```

Layer data has its own name (the name used for bottom, top)

  - Trainable parameters (weight, bias)

```
net.params['conv1/conv'][0].data
net.params['conv1/conv'][1].data
```

Parameter can be accessed via layer's name

  - Their gradients

```
net.blobs['conv1'].diff
net.params['conv1/conv'][0].diff
net.params['conv1/conv'][1].diff
```

  - See python/caffe/_caffe.cpp for whole APIs

```
def compression(true_net, comp_net, cfgs):
  for layer_name in true_net._layer_names:
    if cfgs.has_key(layer_name):
      rank = cfgs[layer_name]
      W_true = true_net.params[layer_name][0].data
      b_true = true_net.params[layer_name][1].data
      W1, b1, W2, b2 = svd(W_true, b_true, rank)
      comp_net.params[layer_name+'_1'][0].data[...] = W1
      comp_net.params[layer_name+'_1'][1].data[...] = b1
      comp_net.params[layer_name+'_2'][0].data[...] = W2
      comp_net.params[layer_name+'_2'][1].data[...] = b2

true_net = caffe.Net('true.pt', 'true.cm', caffe.TEST)
comp_net = caffe.Net('comp.pt', 'true.cm', caffe.TEST)
cfgs = { 'conv1': 8, 'conv2': 16 }
compression(true_net, comp_net, cfgs)
comp_net.save('comp.cm')
```

Python Layer Implementation

```python
import caffe
import numpy as np
import yaml

class NewPythonLayer(caffe.Layer):
  def setup(self, bottom, top):
    # Read & parse parameters
    # You can make any optional auxiliary data
    layer_params = yaml.load(self.param_str)
    self._num_output = layer_params['num_output']
    # Compute & set parameter data shape
    self.blobs.add_blob(...)
    self.blobs.add_blob(...)
    # Initialize parameter data
    self.blobs[0].data[...] = ...
    self.blobs[1].data[...] = ...
```

new_python_layer.py

```python
def reshape(self, bottom, top):
    # Read input data shape
    bottom0_shape = bottom[0].data.shape
    bottom1_shape = bottom[1].data.shape
    # Compute & set output data shape
    top[0].reshape(...)
    top[1].reshape(...)
```

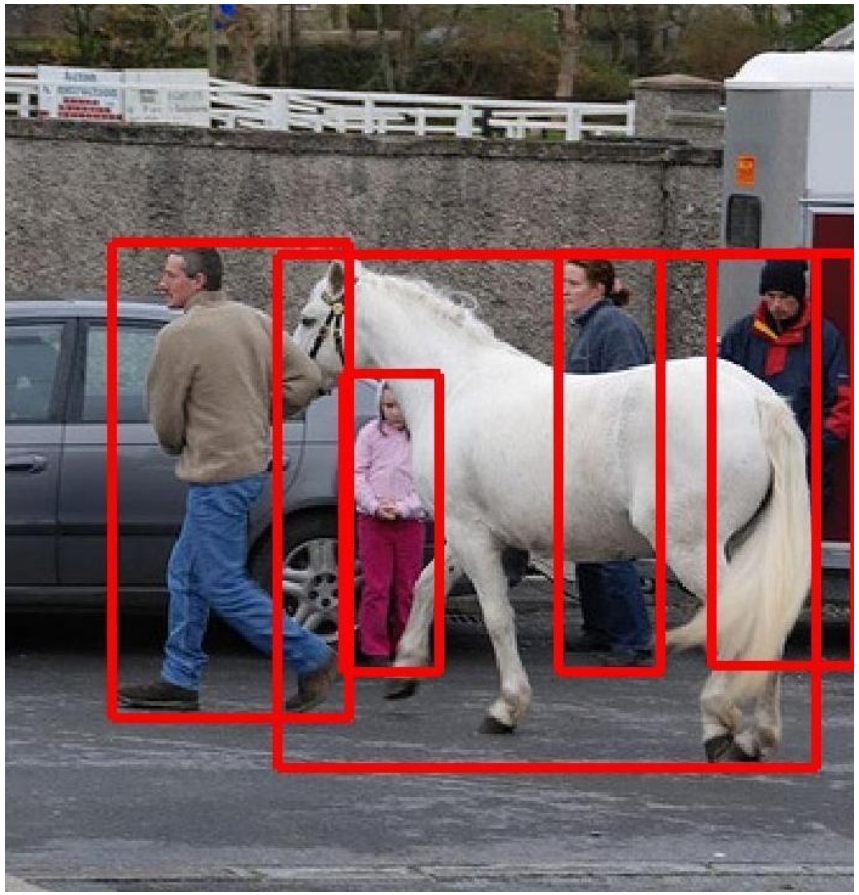
```python
def forward(self, bottom, top):
    # Read input data
    bottom0_data = bottom[0].data
    bottom1_data = bottom[1].data
    # Read parameter data
    weight = self.blobs[0].data
    bias = self.blobs[1].data
    # Compute & store output data
    top[0].data[...] = ...
    top[1].data[...] = ...
```

```python
def backward(self, top, propagate_down, bottom):
    # Read output data gradient
    top0_diff = top[0].diff
    top1_diff = top[1].diff
    # Compute & store parameter data gradient
    self.blobs[0].diff[...] = ...
    self.blobs[1].diff[...] = ...
    # If propagate down,
    # compute & store input data gradient as well
    if propagate_down[0]:
      bottom[0].diff[...] = ...
    if propagate_down[1]:
      bottom[1].diff[...] = ...
```

```
layer {
  name: "op/python"
  type: "Python"
  bottom: "input1"
  bottom: "input2"
  top: "output1"
  top: "output2"
  python_param {
    module: "new_python_layer"
    layer: "NewPythonLayer"
    param_str: "{ 'num_output': 32 }"
  }
}
```

Object Detection

Object Detection?



- Bounding-box prediction
- Classification per box
- Multiple objects in one image
- Overlaps

Data

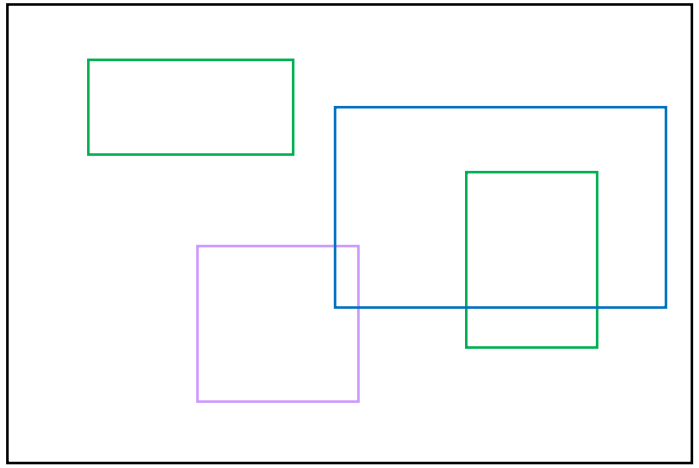
- 1 image + M labels
  - 1 label = class & box
  - M is varying
- VOC-2007
  - Images: VOC2007/JPEGImages
  - Labels: VOC2007/Annotations
  - Index: VOC2007/ImageSet/Main
    - trainval.txt, test.txt

Data Layer

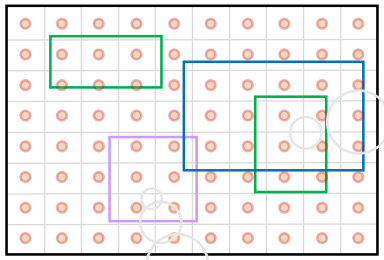
- Parsing 1 .xml and return:
  - Data: 1 x 3 x H x W
  - Label: 1 x (M_1 + M_2 + ... + M_N)
    - $[0,\ x_{\min}, y_{\min},\ x_{\max}, y_{\max}]$

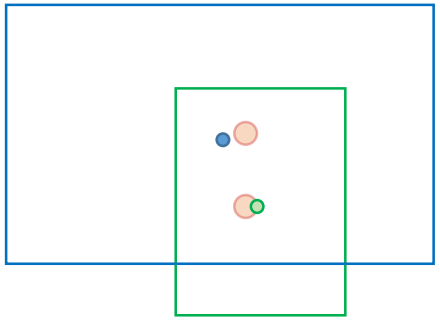
```
~/caffe# export PYTHONPATH=/root/caffe/caffe-materials/practice6:$PYTHONPATH
```

Bounding-Box Prediction

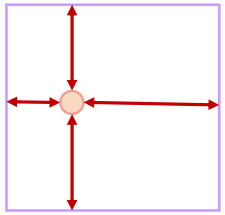


Per-pixel prediction





Overlap handling



Regression: 4 margins

Target Layer

Loss Layer

Clearing Duplicated Predictions

- Non-Maximum Suppression

Results

Summary

- Network design → Data preparation → Training → Testing
  - Building blocks
  - Visualization tool
  - Python network builder
  - Python layer
  - LMDB making & access
  - Visualization
  - Scheduling
  - Network data access
- Some important files
  - src/caffe/proto/caffe.proto
  - python/caffe/_caffe.cpp (`BOOST_PYTHON_MODULE(_caffe){…}`)
  - include/caffe/{net, solver}.hpp, src/caffe/{net, solver}.cpp

Thank You