

Lecture 1:

Computer Structure and Networks for ML

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Lecture Contents

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Part 3: Network and Distributed ML

Part 1/3:

Data Representation and ML Hardware Fundamentals

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- 6.** GPU Cores and CUDA - Understanding Parallel Processing
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ML Workflow and Computer Architecture



Key Impact Areas

- Computer architecture impacts every stage
- Understanding hardware optimizes performance

Critical Bottlenecks

- Data loading efficiency
- Computation speed
- Memory bandwidth limits

Bits and Bytes - Understanding ML Data Types

Fundamental Unit: **1 Byte = 8 Bits**

FP32

Float 32-bit

4 Bytes

PyTorch/TensorFlow default for training

FP16

Float 16-bit

2 Bytes

Half precision, 50% memory

INT8

Integer 8-bit

1 Byte

Quantized, 75% memory savings

Data Type Impact

- Memory usage
- Processing speed
- Model accuracy

Example Calculation:
1B parameters × FP32
= 1B × 4 bytes = 4GB

Byte Representation: Signed vs Unsigned

Unsigned Byte (8-bit)

Signed Byte (8-bit)

Range: 0 to 255

Binary: 00000000 to 11111111

Only positive values

Range: -128 to 127

Uses two's complement

First bit = sign bit

Hexadecimal (Base-16) Representation

1 Byte = 2 Hex Digits (0-9, A-F)

0x00

Decimal: 0

0x0F

Decimal: 15

0x10

Decimal: 16

0xFF

Decimal: 255

ASCII Code Examples

Each character = 1 Byte (8 bits)

A

65 (0x41)

B

66 (0x42)

a

97 (0x61)

0

48 (0x30)

Space

32 (0x20)

Bit-Level Representation

8-bit Integer (INT8)

32-bit Float (FP32)

Decimal: 42

00101010

Decimal: -42 (signed)

11010110

Decimal: 127 (max)

01111111

Structure:

S EEEEEEEE Moooooooooooooooooooooooo

1 Sign bit

8 Exponent bits

23 Mantissa bits

RGB Color Codes and Bytes

Each color channel = 1 Byte (0-255) • Total = 3 Bytes per pixel



Red

#FF0000

RGB(255, 0, 0)



Green

#00FF00

RGB(0, 255, 0)



Blue

#0000FF

RGB(0, 0, 255)



White

#FFFFFF



Gray

#808080



Theme Blue

#1E64C8

RGB(255, 255, 255)

RGB(128, 128, 128)

RGB(30, 100, 200)

Number Representation Methods - Fixed Point vs. Floating Point

Fixed Point

Integer with implicit decimal position

- ✓ Fast computation
- ✓ Limited range
- ✓ Fixed precision

Floating Point

Sign + Exponent + Mantissa

- ✓ Flexible representation
- ✓ Wide range
- ✓ Slower processing

Floating Point Formats

FP32 (32 bits)

Sign: 1 bit

Exponent: 8 bits

Mantissa: 23 bits

Range: $\pm 3.4 \times 10^{38}$

FP16 (16 bits)

Sign: 1 bit

Exponent: 5 bits

Mantissa: 10 bits

Range: $\pm 6.5 \times 10^4$

Key Trade-off

Precision \leftrightarrow Memory \leftrightarrow Speed

Quantization Principles and Memory Efficiency

Quantization: Reducing precision for efficiency

Before

FP32

4 bytes



After

INT8

1 byte

Memory Reduction: 4x smaller (75% savings)

Quantization Methods

- Post-training quantization
- Quantization-aware training

Accuracy Impact

- Minimal accuracy loss
- Typically <1-2% degradation
- With proper quantization

Real-World Applications

Mobile Deployment

Edge Devices

Faster Inference

CPU vs. GPU - Architectural Comparison

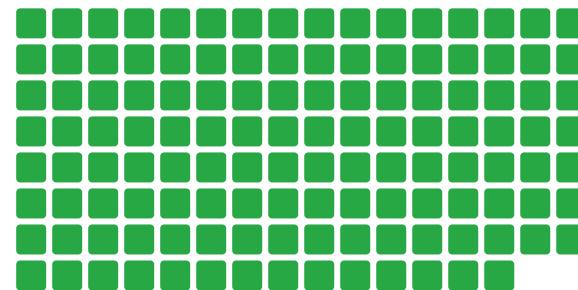
CPU



Few powerful cores (4-64)

- Optimized for sequential tasks
- Better for control flow & branching
- General computing excellence

GPU



Thousands of simple cores (1000s-10000s)

- Massive parallel processing
- 10-100x faster for matrix ops
- Ideal for ML workloads

GPU Performance: **10-100x faster for matrix operations**

Modern ML Workflow

GPU: Training

CPU: Preprocessing / Serving

GPU Cores and CUDA - Understanding Parallel Processing

CUDA: NVIDIA's parallel computing platform (launched 2007)

GPU Architecture Hierarchy

GPU

Graphics Processing Unit



SMs

Streaming Multiprocessors

Example

RTX 4090

Streaming Multiprocessors
128 SMs

CUDA Cores

Cores

CUDA Cores

16,384 cores

SIMT Execution

Single Instruction, Multiple Threads model for parallel processing

Automatic Integration

PyTorch/TensorFlow automatically leverage CUDA kernels

PyTorch & TensorFlow automatically leverage CUDA for GPU acceleration

FLOPS and ML Model Performance Metrics

FLOPS

Floating Point Operations Per Second
Hardware capability metric

FLOPs

Floating Point Operations
Model complexity metric (total operations required)

GPT-3 Training Example

Total FLOPs: $\sim 3.14 \times 10^{23}$ (314 zettaFLOPs)

3.2x faster

NVIDIA A100

312

TFLOPS

NVIDIA H100

1000

TFLOPS

Training Time Calculation

Training Time = Model FLOPs / Hardware FLOPS / GPU Count

Tensor Operations and Hardware Optimization

Tensor: Multi-dimensional array (Foundation of deep learning)

Common Tensor Operations

matmul

Matrix multiplication

Parallelizable

conv2d

2D convolution

Parallelizable

attention

Self-attention

Parallelizable

Coalesced Access



Sequential memory reads

⚡ Fast & efficient

Uncoalesced Access



Random memory reads

⚠ Slow & inefficient

Optimization Strategies

- ✓ Batch operations together
- ✓ Maintain contiguous memory

Tensor Cores

Specialized hardware for mixed-precision
matmul

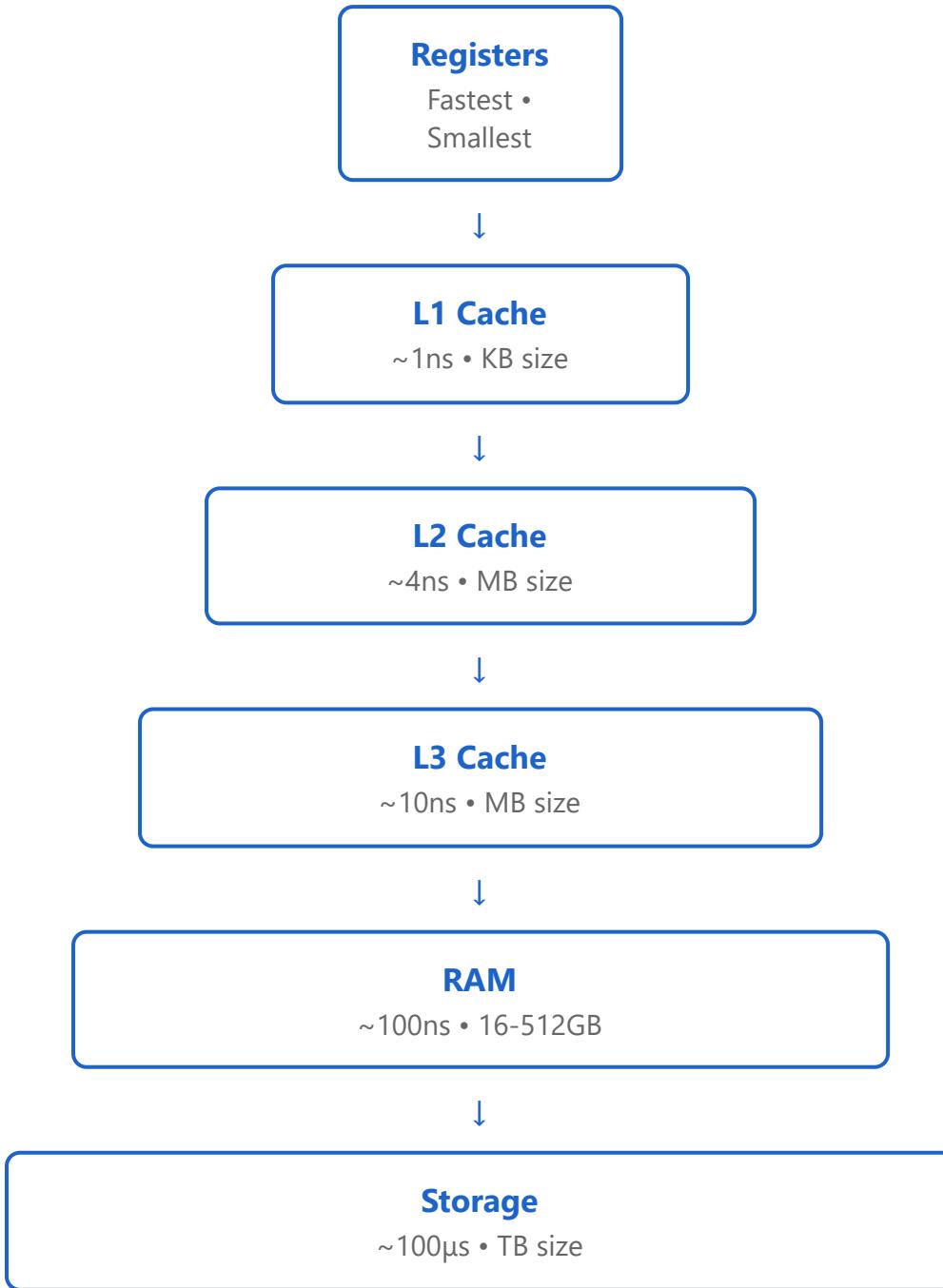
✓ Minimize CPU-GPU transfers

Part 2/3:

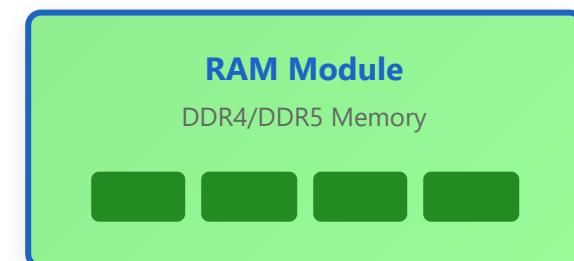
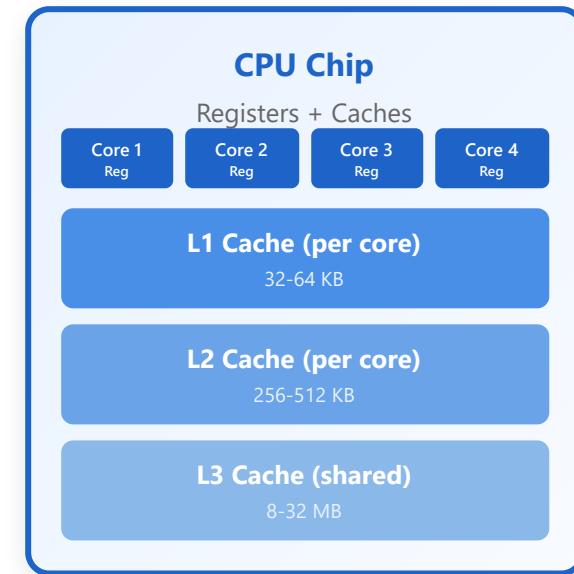
Memory and ML Model Execution

- 9.** Memory Hierarchy - RAM, VRAM, Cache
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- 13.** Memory Layout of NumPy/PyTorch Tensors
- 14.** GPU Memory Management
- 15.** Mixed Precision Training - FP16 and FP32
- 16.** Hands-on: Resource Monitoring Tools

Memory Hierarchy - RAM, VRAM, Cache



Physical Hardware Components



RAM

16-512GB

~20GB/s bandwidth

System memory

VRAM (GPU)

8-80GB

~1-2TB/s bandwidth

HBM2/HBM3

Cache

L1: KB

L2: MB

L3: MB

ML Bottleneck:

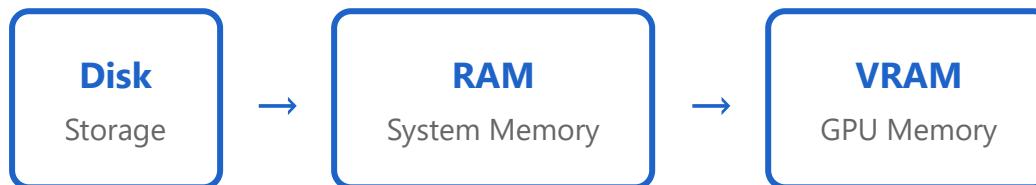
RAM



VRAM

Data transfer overhead

ML Models Loading and Memory Management



Challenge: LLaMA-70B = 140GB (FP16) exceeds single GPU VRAM

Solutions for Large Models

1

Model Sharding

Distribute across multiple GPUs
(tensor parallelism)

2

Offloading

Keep parameters in RAM, load
when needed

3

Quantization

Reduce memory footprint (8-bit,
4-bit)

Key Insights

- Memory bandwidth limits loading speed
- Disk I/O is not the bottleneck
- Use memory-mapped files (mmap)

Popular Tools

- Hugging Face Accelerate
- DeepSpeed ZeRO

Batch Size and Memory Usage Calculation

Memory Usage Components

Model Params

+

Optimizer States

+

Gradients

+

Activations

Activations Memory \propto **Batch Size \times Sequence Length**

Example: BERT-base

batch = 32 • **seq = 512** → **~8GB** activation memory

Gradient Accumulation

Split batch into micro-batches to save memory

Gradient Checkpointing

Recompute activations (trade compute for memory)

Rule of Thumb

OOM Error?

Reduce batch size by 50%

Monitoring Tools

nvidia-smi

`torch.cuda.memory_allocated()`

```
$ nvidia-smi
```

```
+-----+  
| NVIDIA-SMI 535.104.05   Driver Version: 535.104.05   CUDA Version: 12.2 |
```

GPU	Name	Persistence-M	Bus-Id	Disp.A	Volatile	Uncorr.	ECC
Fan	Temp	Perf	Pwr:Usage/Cap	Memory-Usage	GPU-Util	Compute M.	
0	NVIDIA A100-SXM...	On	00000000:00:04.0	Off	0		
N/A	45C	P0	215W / 400W	18432MiB / 40960MiB	78%	Default	

Processes:							
GPU	GI	CI	PID	Type	Process name	GPU Memory	
	ID	ID				Usage	
0	N/A	N/A	12345	C	python train.py	18420MiB	

Python Bytecode and ML Frameworks

Python Execution Flow

Python Code



Bytecode



VM Execution

ML Framework Architecture

Frontend

Python API



Backend

C++ / CUDA

Eager Mode

Default

- Flexible execution
- Good for debugging
- Slower performance

Graph Mode

Optimized

- Pre-compiled graph
- Faster execution
- Production ready

JIT Compilation

`torch.jit.script()` speeds up inference via Just-In-Time compilation

TorchScript

Serialize models for production (remove Python dependency)

Real Performance

CUDA kernels drive performance, not Python code

Python Overhead

Negligible for large tensor operations (batching helps)



Interactive Interpreter Execution

1 Python Source Code

```
def add(a, b):\n    return a + b\n\nresult = add(3, 5)\nprint(result)
```

2 Bytecode

3 VM Execution

Stack:

```
[ ]
```

Variables:

```
{ }
```

Output:

```
-
```

◀ Previous

Step 1 / 9

Next ▶

⟳ Reset

Step 1: Python Source Code

We define a simple Python function and call it. This code creates an add function that takes two numbers, then passes 3 and 5 as arguments and prints the result.

Memory Layout of NumPy/PyTorch Tensors

Tensors: Multi-dimensional arrays stored in **contiguous memory**

Row-Major (C)

Default

Last dimension varies fastest

0,0

0,1

1,0

1,1

Column-Major (Fortran)

First dimension varies fastest

0,0

1,0

0,1

1,1

Stride

Number of bytes to jump to next element in each dimension

Contiguous Tensors ✓

- ✓ Faster operations
- ✓ Better cache locality
- ✓ Optimized GPU performance

Non-Contiguous △

- ⚠ After transpose(), view()
- ⚠ May need .contiguous()
- ⚠ Slower memory access

Memory Layout Impact

- Cache hits efficiency
- Vectorization performance
- GPU operation speed

Check Methods

`.is_contiguous()`
`.stride()`

GPU Memory Management

GPU Memory Allocation

Cached allocator for efficiency (PyTorch)

Free unused cache: `torch.cuda.empty_cache()`

✓ Best Practices

- ✓ Allocate tensors at beginning
- ✓ Reuse tensors when possible
- ✓ Minimize CPU↔GPU transfers

⚠ Avoid

- ✗ Creating tensors in loops
- ✗ Frequent CPU↔GPU transfers
- ✗ Memory fragmentation

Transfer Speed Comparison

Within GPU (device-to-device)

Fast

Between GPUs

Slow

Unified Memory (CUDA)

Automatic migration between CPU and GPU memory

Profiling Tools

- PyTorch Profiler
- NVIDIA Nsight Systems

Mixed Precision Training - FP16 and FP32

Mixed Precision: Use **FP16 for compute , FP32 for stability**



Memory Reduction

2x smaller



Speed Boost

2-3x faster

(with Tensor Cores)



Challenge

✓ Solution

FP16 range limited → gradient underflow/overflow issues

Loss scaling: multiply loss by 1000-10000 to prevent underflow

Master Weights Strategy

FP32 Master Copy



FP16 Forward/Backward



FP32 Updates

AMP Tools

`torch.cuda.amp`

`TF mixed_precision`

Best Hardware

Modern GPUs (Volta+) with Tensor Cores

Accuracy Impact

Minimal loss (<0.1%) for significant speedup

Hands-on: Resource Monitoring Tools



GPU Monitoring

```
nvidia-smi
```

Real-time GPU utilization, memory, temperature

```
watch -n 1 nvidia-smi
```

Auto-refresh every second



CPU & System

```
htop / top
```

CPU and system memory monitoring

PyTorch Memory Tools

```
torch.cuda.memory_summary()
```

```
torch.cuda.memory_allocated()
```

TensorBoard

Visualize training metrics & memory over time

NVIDIA Nsight

Detailed profiling of GPU operations

W&B / MLflow

Track experiments & resource usage



Practice Workflow

Monitor during training



Identify bottlenecks



Optimize

Part 3/3:

Network and Distributed ML

- 17.** IP Addresses and Ports - Server Connection Basics
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- 19.** File Transfer - Using SCP and SFTP
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IP Addresses and Ports - Server Connection Basics

IPv4

32-bit address

4.3 billion addresses

192.168.1.100

IPv6

128-bit address

Future-proof

2001:0db8::1

Public IP

Internet-facing address, globally unique

Private IP

Internal network (192.168.x.x, 10.x.x.x)

Common Ports (0-65535)

22

SSH

80

HTTP

443

HTTPS

ML Server Connection

```
ssh user@192.168.1.100 -p 22
```

Port Forwarding

Firewall

Security

Access remote Jupyter: localhost:8888
→ server:8888

Controls port accessibility from outside

Use non-standard ports, close unused ports

SSH and Remote Server Connection Practice

SSH (Secure Shell): Encrypted remote terminal access to servers



Basic Connection

```
ssh username@hostname
```

SSH Key Authentication Setup (More Secure)

1

Generate Keys

```
ssh-keygen -t rsa -b 4096
```

2

Copy Public Key

```
ssh-copy-id username@server
```

3

Connect

```
ssh username@server
```

No password needed!

SSH Config

Persistent Sessions

Practice

Connect to lab server, run training scripts remotely

`~/.ssh/config` for convenient
aliases and settings

Use `tmux` or `screen` to keep
sessions alive

File Transfer - Using SCP and SFTP

SCP (Secure Copy): Command-line file transfer over SSH

↑ **Upload**

Local → Remote Server

```
scp local_file.py user@server:/remote/path/
```

↓ **Download**

Remote Server → Local

```
scp user@server:/remote/model.pth ./local/path/
```

Recursive Transfer (Entire Directories)

Use -r flag to transfer directories

```
scp -r ./dataset/ user@server:/data/
```

SCP

Simple command-line transfer over SSH

SFTP

Interactive file transfer (like FTP but secure)

rsync

Smart sync, only transfers changed files (efficient)

Large Datasets

Consider cloud storage (S3, GCS) or shared filesystems

Compression Tip

Compress before transfer (tar + gzip) for faster upload/download

HTTP API and Model Serving

REST API: Standard way to serve ML models over HTTP

Client Request

POST /predict
JSON data

ML Model

Processing
Inference

Server Response

JSON
predictions

Popular Frameworks

Flask

FastAPI

TensorFlow Serving

✓ Benefits

- Language-agnostic
- Easy integration
- Scalable with load balancers

⚠ Considerations

- Latency (~10-100ms)
- Throughput (requests/sec)
- Batching strategies

Production Tools

Docker + Kubernetes for deployment and scaling

Monitoring

Track API response time, error rates, model accuracy drift

Distributed Training Overview

Why Distributed? Single GPU insufficient for large models/datasets

Data Parallelism



Same model on multiple GPUs, different data batches

Model Parallelism



Split model across GPUs (layers or tensor sharding)

Synchronous Training

Common

All GPUs sync gradients each step. More stable, consistent results.

Asynchronous Training

GPUs update independently. Faster but less stable convergence.

PyTorch Standard Implementation

DistributedDataParallel (DDP) for multi-GPU training

`torch.nn.parallel.DistributedDataParallel`

Communication

All-reduce operation for gradient synchronization across GPUs

Efficiency

Linear speedup ideal (2 GPUs = 2x), but overhead exists

Network Bandwidth and Learning Speed

Network Bandwidth: Critical for multi-node distributed training

Single Node

Fast

8 GPUs with NVLink/PCIe

Direct GPU communication

Multi-Node

Moderate

Ethernet: 10-100 Gbps

InfiniBand: 200-400 Gbps

Network dependent

Communication Bottleneck Example

Increases with more nodes and smaller batches

Gradient sync time > Computation time = Bottleneck

Gradient Compression

Reduce data to transfer

Reduce Frequency

Communicate less often

ZeRO (DeepSpeed)

Partition optimizer states

⚡ Design Rule

Network bandwidth should match GPU compute capability

NVLink

600 GB/s

GPU-to-GPU direct

High-end servers

PCIe 4.0 x16

32 GB/s

Most common setup

Standard

PCIe 5.0 x16

64 GB/s

Latest generation

Emerging

Docker Basics - ML Environment Containerization

Docker: Package application + dependencies into portable container

✓ Consistent environment • No "works on my machine" issues



Image

Template (read-only)

`pytorch/pytorch:2.0-cuda11.8-cudnn8-runtime`



Container

Running instance of image (isolated process)



Dockerfile

Recipe to build custom images



Volume

Mount local directory for data persistence

Dockerfile Commands

FROM

RUN

COPY

CMD

🤔 Without Docker vs With Docker

✗ Without Docker

✓ With Docker



Computer A



Computer B

see the differ

Start Comparison

Reset

Leveraging Cloud GPUs

Major Cloud Providers

AWS

EC2 P4/P5

GCP

A2/A3

Azure

NC/ND series

On-Demand

\$\$\$\$

Pay per hour - Expensive but flexible

e.g., \$32/hr for A100

Spot Instances

70-90% off

Much cheaper, can be interrupted

Good for experiments

Managed Services

- SageMaker (AWS)
- Vertex AI (GCP)
- Azure ML

GPU Marketplaces

- Lambda Labs
- RunPod
- Vast.ai

Cost Optimization

Small GPUs for debug, scale up for training

Free Credits

Research/education credits from providers

Always Shut Down

Stop instances when not in use, monitor spending

Hands-on Project - Training ML Models on Remote Server

Project Goal: Train image classifier on remote GPU server

1 SSH & Setup

SSH into server and setup environment
(conda/docker)

2 Transfer Dataset

Use scp or download directly on server

3 Write Training Script

PyTorch/TensorFlow with proper logging

4 Run in tmux

Persistent session even if disconnected

5 Monitor Training

nvidia-smi and TensorBoard (port forwarding)

6 Download & Evaluate

Download trained model and evaluate locally

Project Deliverables



Working Model



Training Logs



Results Presentation

Thank you

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