

STAT 4830: Numerical optimization for data science and ML

Lecture 0: Introduction

Professor Damek Davis

Course overview

- **Focus:** Numerical optimization for data science and ML
- **Tools:** PyTorch, Python, occasional use of other libraries
- **LLM Policy:** Use them.
- **Deliverables:** Weekly assignments, final project
 - **Homework:** 0-5 assignments.
 - **Final Project:** Incrementally developed throughout semester.

Do you have access to and experience with LLMs?

Modern optimization and ML development fundamentally requires AI assistance for:

- Debugging complex numerical code*
- Exploring implementation alternatives*
- Understanding mathematical concepts*
- Rapid prototyping of algorithms*

Without these tools, students would:

- 1. Struggle with industry-standard development practices*
- 2. Miss critical job-market skills*
- 3. Face unnecessary friction in learning core concepts*

The course focuses on practical implementation - AI assistance isn't optional, its core to modern development workflows.

Prerequisites

- Basic calculus and linear algebra (Math 2400)
- Basic probability (Stat 4300)
- Python programming experience
- No advanced optimization/ML background needed

Why PyTorch?

- Modern auto-differentiation frameworks drive deep learning success
- Enables rapid experimentation with:
 - New model architectures and
 - Novel optimization algorithms
- More flexible than traditional solver-based tools

Optimization Approaches Compared

CLASSICAL TOOLS	VS	MODERN TOOLS
WHEN TO USE: <ul style="list-style-type: none">• Small/Medium Scale• Structured Problems• Need Formal Guarantees		WHEN TO USE: <ul style="list-style-type: none">• Large-Scale Data• Unstructured Problems• Need Speed & Scale
INPUT REQUIREMENTS: <ul style="list-style-type: none">• DCP Rules• Convex Functions• Standard Form		INPUT REQUIREMENTS: <ul style="list-style-type: none">• Raw Python Code• Any Function Type• Black Box OK
GUARANTEES: <ul style="list-style-type: none">• Global Optimality• Convergence Rates• Optimality Certificates		CAPABILITIES: <ul style="list-style-type: none">• Handle Any Problem• Fast Development• Rapid Iteration
WORKFLOW: <ol style="list-style-type: none">1. Format Problem2. Verify Convexity3. Solve Exactly		WORKFLOW: <ol style="list-style-type: none">1. Write Code2. Train Model3. Debug & Iterate
TOOLS: CVX, MOSEK		TOOLS: PyTorch, JAX

HYBRID APPROACHES:

- Use Structure Where Possible
- Add Flexibility Where Needed
- Choose Based on Requirements

Preview: spam classification

Let's start with a practical example:

- How do we automatically filter spam emails?
- Demonstrates core optimization concepts
- Shows PyTorch in action

How computers read email

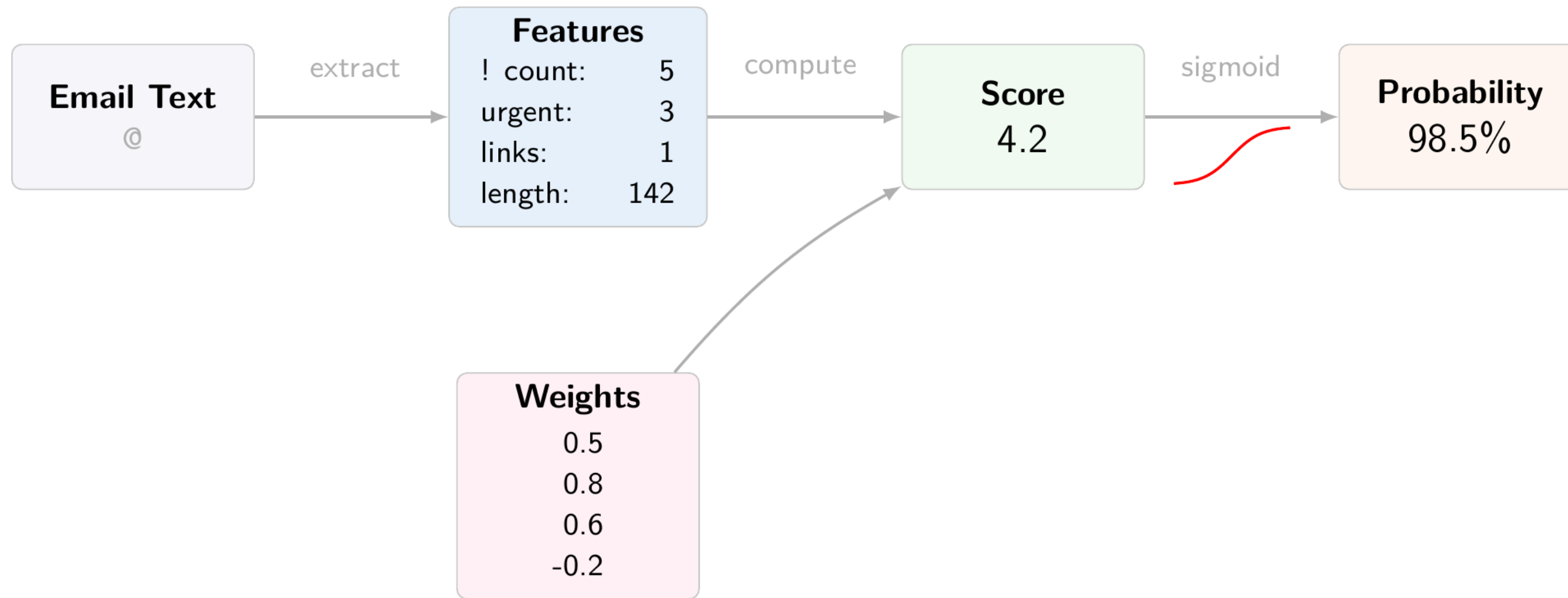
```
email1 = """  
Subject: URGENT! You've won $1,000,000!!!  
Dear Friend! Act NOW to claim your PRIZE money!!!  
"""  
  
email2 = """  
Subject: Team meeting tomorrow  
Hi everyone, Just a reminder about our 2pm sync.  
"""
```


Feature extraction

Convert text to numbers:

```
def extract_features(email):  
    features = {  
        'exclamation_count': email.count('!'),  
        'urgent_words': len(['urgent', 'act now', 'prize']  
                             & set(email.lower().split())),  
        'suspicious_links': len([link for link in email.split()  
                                 if 'www' in link]),  
        'time_sent': email.timestamp.hour,  
        'length': len(email)  
    }  
    return features
```

Classification process

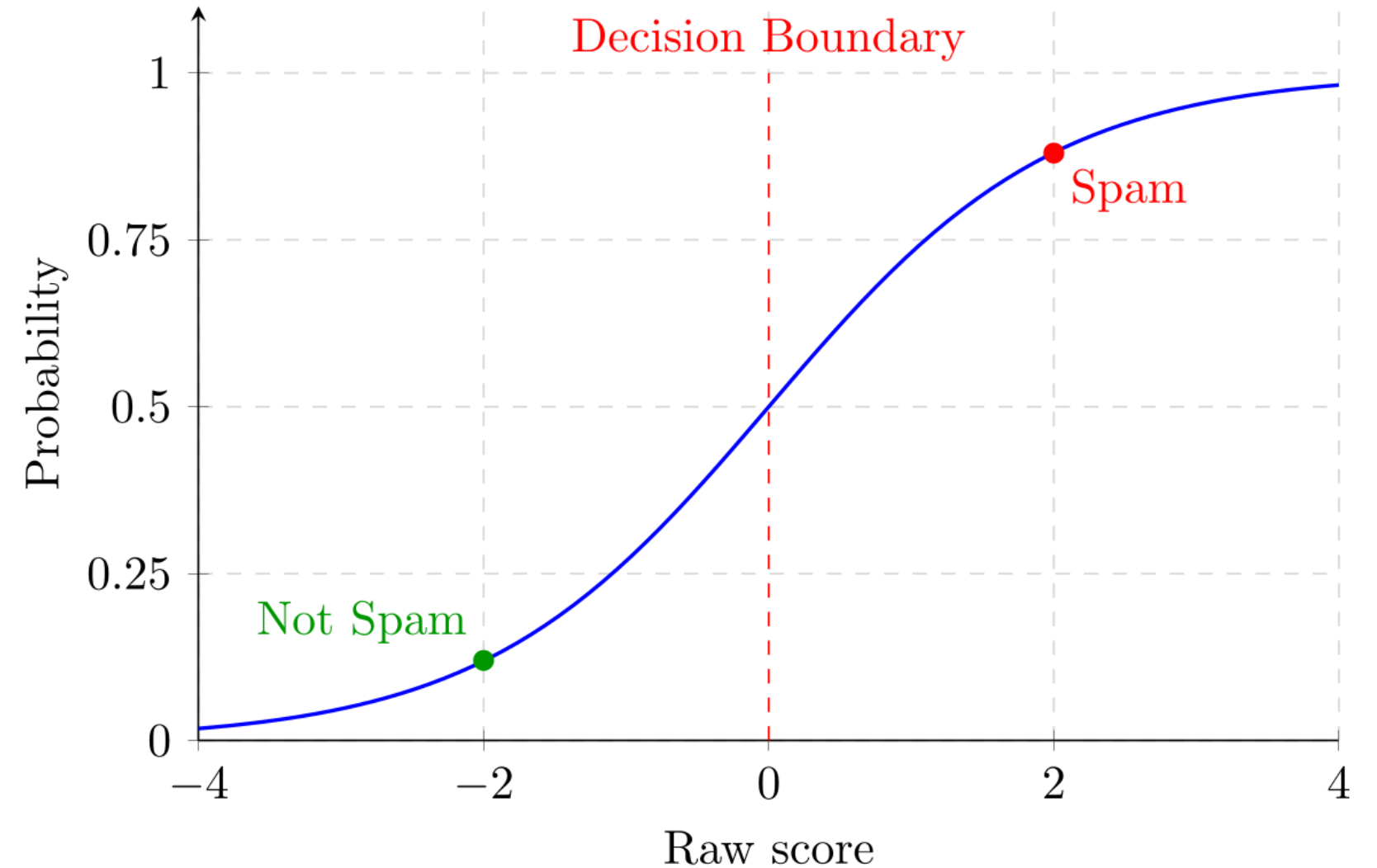


1. Extract numeric features
2. Multiply by weights
3. Sum weighted features
4. Convert to probability

The sigmoid function

Converts any number into a probability (0-1):

```
def sigmoid(x):  
    return 1 / (1 + torch.exp(-x))
```



Mathematical formulation

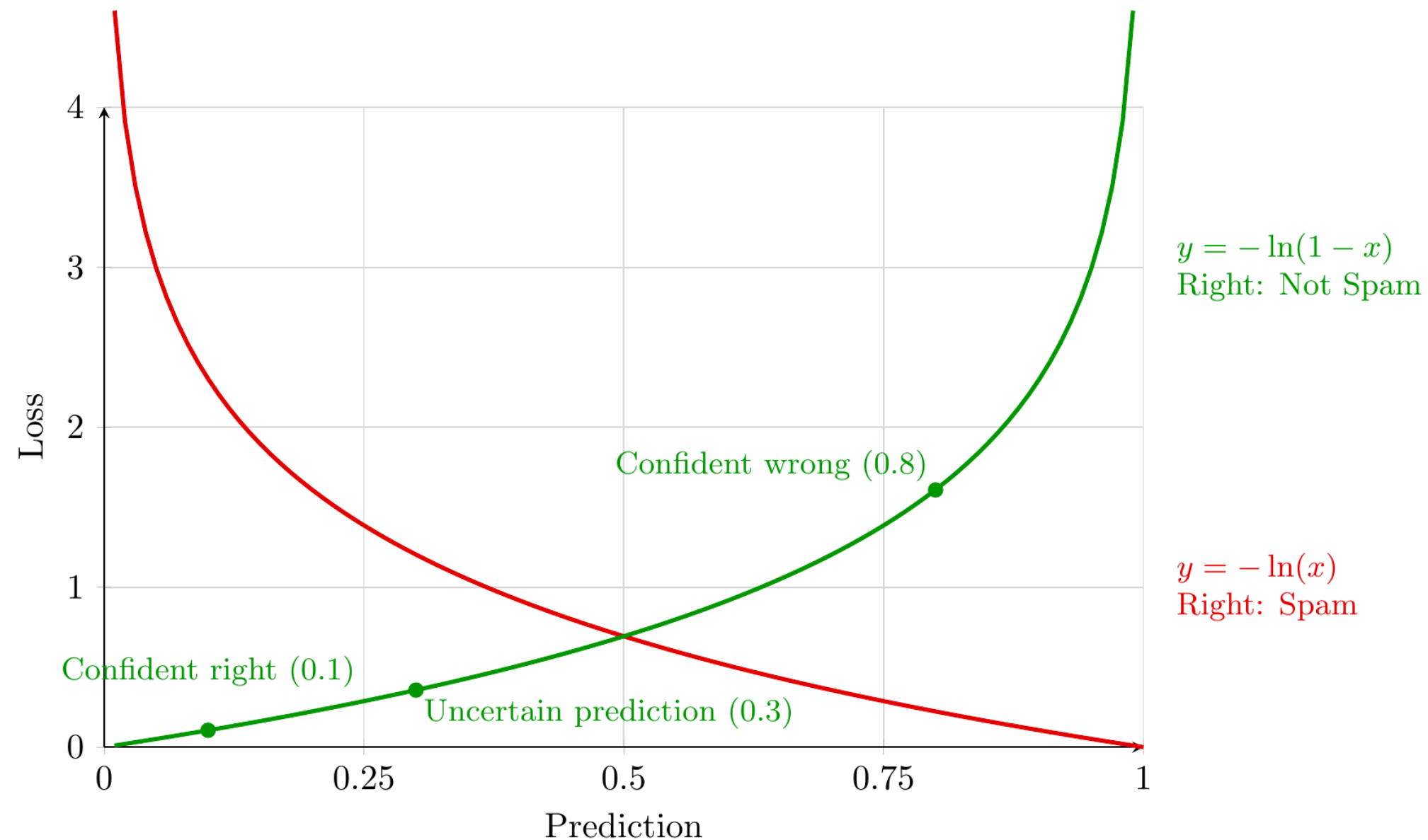
Our optimization problem:

$$\min_w \frac{1}{n} \sum_{i=1}^n \left[-y_i \log(\sigma(x_i^\top w)) - (1 - y_i) \log(1 - \sigma(x_i^\top w)) \right]$$

Where:

- w = weights vector
- x_i = feature vector
- y_i = true label (0/1)
- σ = sigmoid function

Cross-entropy loss

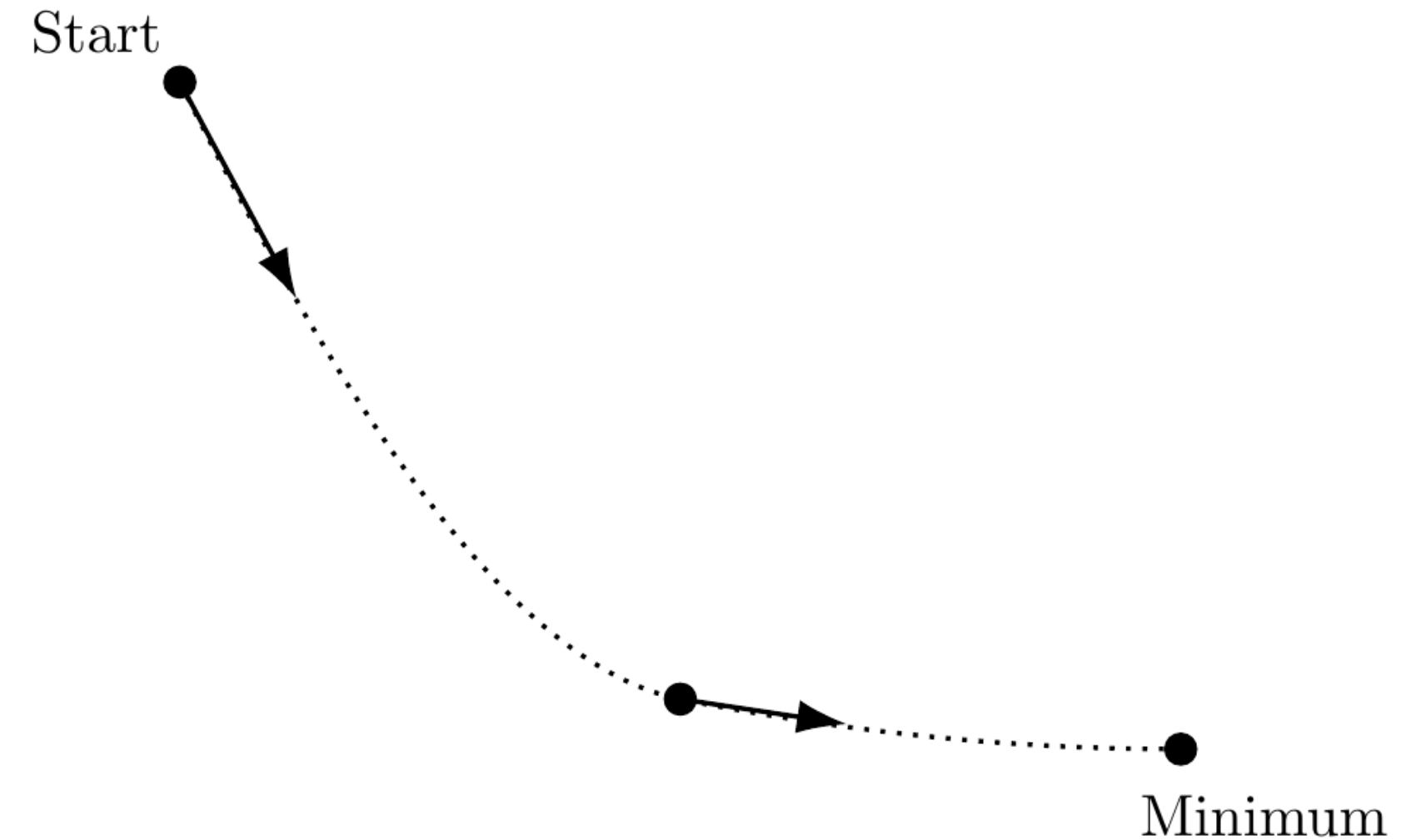


- Penalizes wrong predictions
- Rewards confident correct predictions
- Creates balanced learning

How Gradient Descent Works

The optimization process works like hiking:

1. Look around you (measure gradient)
2. Take a step downhill
3. Repeat until you reach the bottom



The optimization loop

Each iteration:

1. **Measure** how well current weights classify emails
2. **Calculate** gradient (direction of steepest error reduction)
3. **Update** weights by stepping in this direction
4. **Repeat** until convergence

The learning rate controls step size:

- Too small → slow progress
- Too large → overshooting

PyTorch: What, how, and why

What: Modern framework for optimization and deep learning

How:

- Tracks operations in a computational graph
- Automatically computes gradients
- Enables parallel computation (CPU/GPU)

Why:

- Automates the hardest part (gradients)
- Makes experimentation fast
- Scales from simple to complex models

Inside PyTorch: Tensors and autograd

```
# Tensors: The building blocks  
x = torch.tensor([1.0, 2.0], requires_grad=True)  
y = x * 2  
z = y.sum()  
  
# Automatic differentiation  
z.backward() # Computes gradients  
print(x.grad) # Shows  $\partial z / \partial x$ 
```

PyTorch builds a graph of operations, enabling automatic gradient computation.

Implementation in PyTorch

```
# Initialize
weights = torch.randn(5, requires_grad=True)
learning_rate = 0.01

for _ in range(1000):
    # Forward pass
    predictions = spam_score(features, weights)
    loss = cross_entropy_loss(predictions, true_labels)

    # Backward pass
    loss.backward()

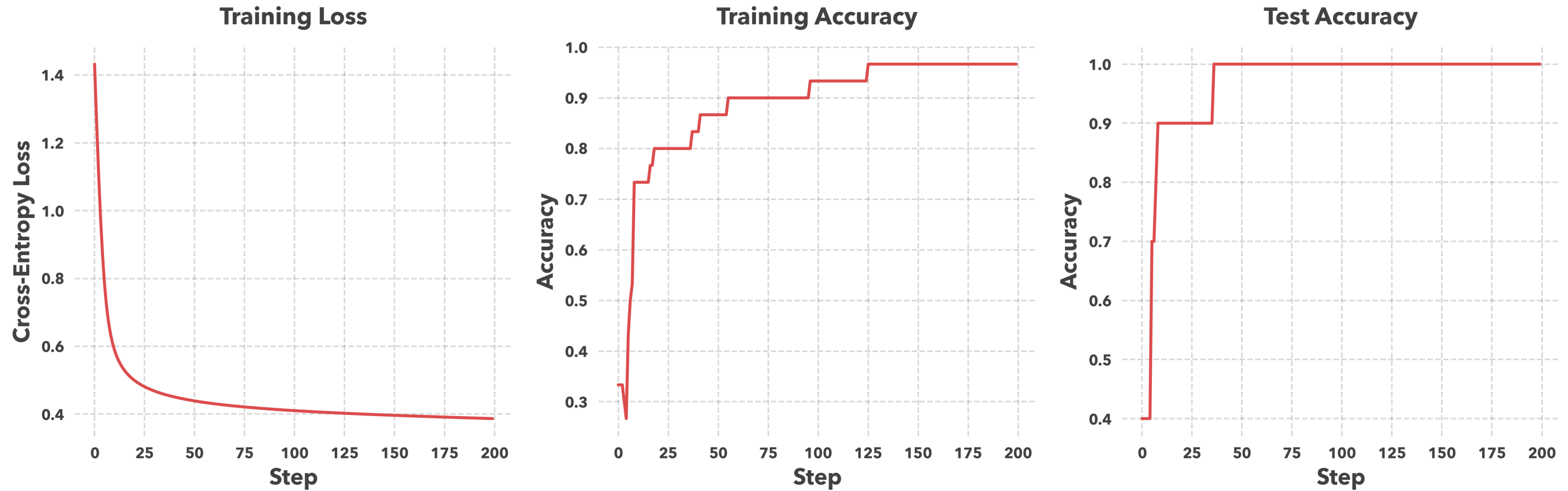
    # Update weights
    with torch.no_grad():
        weights -= learning_rate * weights.grad
        weights.grad.zero_()
```

Try it yourself!

 Open in Colab

- Complete implementation in the notebook
- Experiment with different learning rates
- See how the loss changes during training
- Test the model on new emails

Training results



Three key metrics:

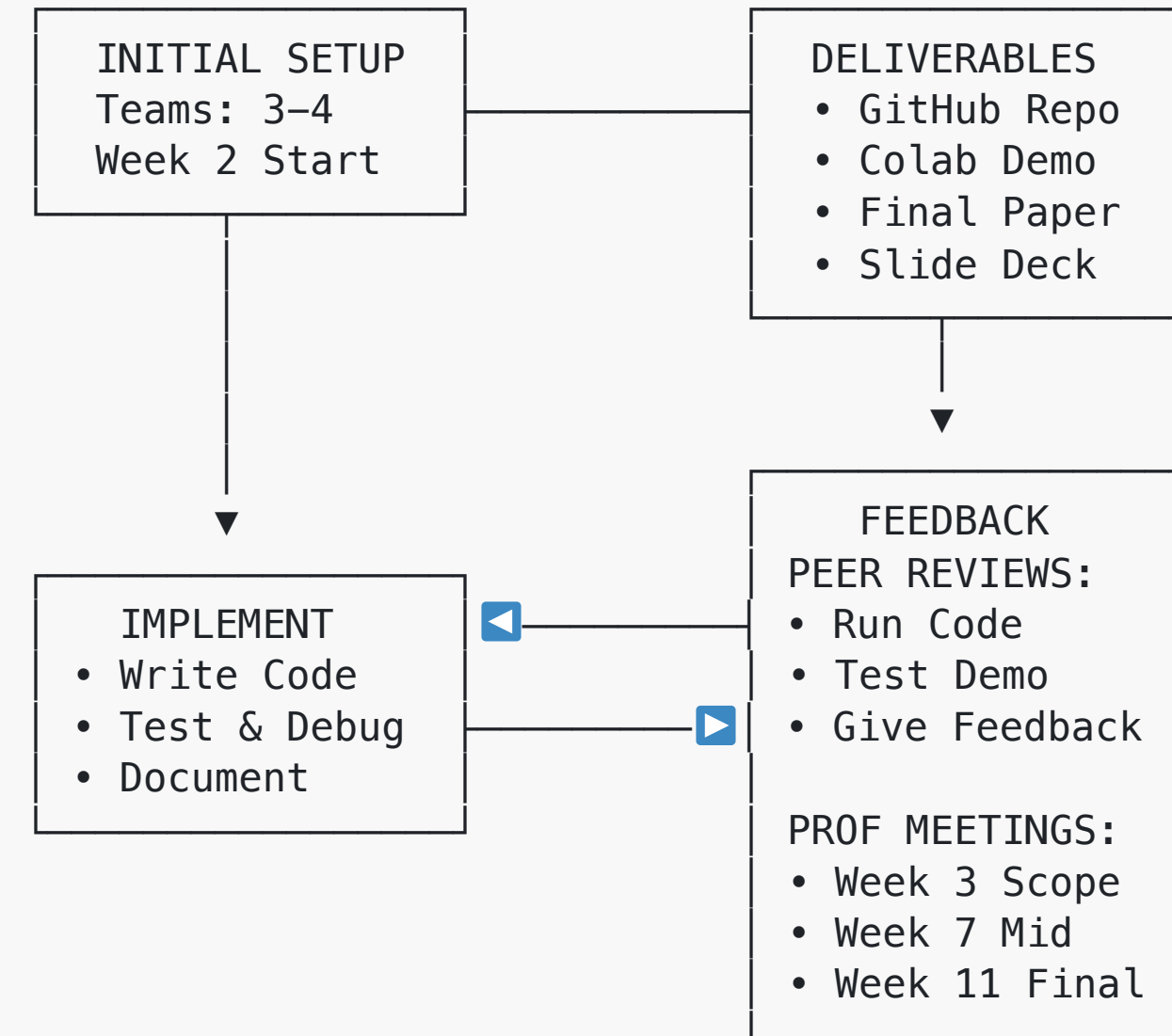
- **Loss** and **Training accuracy:** Performance on known data.
- **Test accuracy:** Performance on new emails

Course structure

1. Linear algebra & direct methods
2. Problem formulations & classical software
3. Calculus for optimization
4. Automatic differentiation & PyTorch
5. First-order methods
6. Second-order methods
7. Advanced topics
8. Modern deep learning practice

Final Project Structure

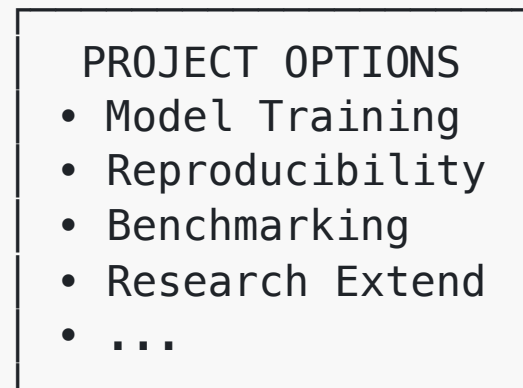
ITERATIVE DEVELOPMENT PROCESS



DEVELOPMENT WITH LLMs

- Write & review reports, documentation
- Develop & test code (verify outputs!)
- Regular commits with clear documentation

PROJECT COMPONENTS



BIWEEKLY SCHEDULE

Week 3: Report
Week 4: Slides Draft
Week 5: Report
Week 6: Slides Draft
Week 7: Report
Week 8: ⚡LIGHTNING TALK⚡
Week 9: Report
Week 10: Slides Draft
Week 11: Report
Week 12: Slides Draft
Week 13: Final Report
Week 14: Final Present

Learning outcomes

By course end, you'll be able to:

1. Model real problems as optimization problems
2. Select appropriate algorithms
3. Implement solutions in PyTorch
4. Apply optimization to practical problems
5. Conduct optimization research

Getting started

- Review the syllabus
- Set up Python environment
- Try the [Colab notebook](#)
- Start thinking about project ideas

Questions?

- Course website: <https://damek.github.io/STAT-4830/>
- Office hours: Listed on the course website
- Email: damek@wharton.upenn.edu
- Discord: Check email for invite.

