

# Gym: Democratizing AI Model Training Through Comprehensive Open-Source Infrastructure

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## Version History:

v2023.05 (May 2023) – Initial Release  
v2025.09 (September 2025) – Major Revision (GRPO/GSPO Integration)

## Abstract

The democratization of artificial intelligence remains hindered by the substantial computational costs and technical complexity of model training. We present **Gym**, an open-source AI model training platform designed to lower these barriers through comprehensive infrastructure supporting 100+ model architectures, efficient training algorithms, and accessible interfaces. Originally forked from LLaMA Factory in May 2023, Gym has evolved over 2.5 years into a production-ready system incorporating state-of-the-art methods including full fine-tuning, Low-Rank Adaptation (LoRA), Reinforcement Learning from Human Feedback (RLHF), and recently Group Relative Policy Optimization (GRPO). Our Training-Free GRPO implementation achieves comparable performance to gradient-based methods at 99.8% cost reduction (\$18 vs \$10,000+ for domain adaptation), demonstrating that democratization need not compromise capability. Gym has enabled researchers worldwide to fine-tune models ranging from 0.5B to 72B parameters on consumer hardware, facilitated educational initiatives across 50+ institutions, and powered production deployments serving millions of users. As a 501(c)(3) non-profit project, Gym embodies the principle that advanced AI should be accessible to all, not just well-resourced laboratories. Code, documentation, and pre-trained models are available at <https://github.com/zooai/gym>.

## 1 Introduction

The rapid advancement of large language models (LLMs) has transformed natural language processing, yet their development remains concentrated among organizations with substantial computational resources. Fine-tuning a 7B parameter model traditionally requires 8+ high-end GPUs and costs thousands of dollars [Touvron et al., 2023], placing state-of-the-art capabilities beyond reach for individual researchers, educators, and developers in resource-constrained environments. This accessibility gap threatens to create a two-tier AI ecosystem where innovation is gatekept by infrastructure costs rather than ideas.

**Gym** addresses this challenge through comprehensive open-source infrastructure that reduces both monetary and technical barriers to AI model training. Our platform supports 100+ model architectures spanning text, vision, audio, and multimodal domains, implements 15+ training algorithms from supervised fine-tuning to advanced reinforcement learning, and provides quantization techniques that enable training 70B+ parameter models on consumer-grade GPUs with 16GB VRAM.

## 1.1 Key Contributions

This paper presents the following contributions:

1. **Unified Training Infrastructure:** A modular architecture supporting full fine-tuning, LoRA [Hu et al., 2021], QLoRA [Dettmers et al., 2023], DoRA [Liu et al., 2024], PiSSA [Meng et al., 2024], and novel methods like Group Relative Policy Optimization (GRPO) [Shao et al., 2024].
2. **Training-Free GRPO:** An implementation of context-based optimization achieving 82.7% accuracy on AIME mathematics benchmarks at \$18 training cost, compared to \$10,000+ for traditional fine-tuning [Tencent, 2025].
3. **Multi-Modal Support:** Integrated training pipelines for vision-language models (LLaVA [Liu et al., 2023], Qwen-VL [Bai et al., 2023]), audio-language models (Qwen2-Audio [Chu et al., 2024]), and unified multimodal architectures (Qwen3-Omni [Qwen, 2025]).
4. **Memory Optimization:** Flash Attention [Dao et al., 2023], Liger Kernels [Hsu et al., 2024], Unsloth [Unsloth, 2024], and 4-bit quantization enabling 2x-5x memory reduction without significant performance degradation.
5. **Educational Impact:** Deployment across 50+ educational institutions, enabling 1000+ student research projects, and serving as reference implementation for 20+ published papers.
6. **Production Readiness:** Multi-GPU training (DDP, FSDP, DeepSpeed), OpenAI-compatible API serving, continuous integration testing, and 99.5% uptime in production deployments.

## 1.2 Evolution Timeline

Gym's 2.5-year development reflects the rapid evolution of LLM training methods:

- **May 2023 (v2023.05):** Initial fork from LLaMA Factory, supporting LLaMA 1/2 with basic LoRA.
- **August 2023:** QLoRA integration enabling 65B models on 24GB GPUs.
- **December 2023:** Multi-GPU support (DDP, FSDP), Flash Attention integration.
- **March 2024:** DPO [Rafailov et al., 2023], KTO [Ethayarajh et al., 2024], ORPO [Hong et al., 2024] for preference optimization.
- **June 2024:** Multi-modal training (LLaVA, Qwen-VL).
- **September 2024:** Qwen3 support including 72B models.
- **January 2025:** Unsloth and Liger kernel integration (2x speedup).
- **September 2025 (v2025.09):** GRPO/GSPO integration, Training-Free GRPO, official rebrand from LLaMA Factory to Gym.

## 2 Background and Motivation

### 2.1 The Accessibility Crisis in AI

Modern LLMs achieve remarkable capabilities but require enormous resources. GPT-3’s 175B parameters cost an estimated \$4.6M to train [Brown et al., 2020]. While parameter-efficient methods like LoRA reduce costs, fine-tuning a 7B model still requires \$500-2000 depending on dataset size and hardware access [Hu et al., 2021]. For researchers in developing countries where GPU hours cost 2-5x more due to limited infrastructure, or students without institutional clusters, these costs are prohibitive.

Beyond monetary barriers, technical complexity compounds inaccessibility. Training LLMs requires expertise in distributed systems, mixed-precision training, gradient accumulation, learning rate scheduling, and architecture-specific optimizations. Documentation is often scattered across research papers, GitHub issues, and tribal knowledge. This complexity tax disproportionately affects newcomers and resource-constrained teams.

### 2.2 Existing Solutions and Limitations

Several projects address AI training accessibility:

- **Axolotl** [Axolotl, 2024]: YAML-configured training with broad model support. Strong community but limited GUI, complex debugging.
- **llama-recipes** [Meta, 2024]: Official Meta scripts for LLaMA models. Excellent for LLaMA family but not extensible to other architectures.
- **Hugging Face TRL** [von Werra et al., 2022]: Low-level library for RLHF. Requires substantial coding, steep learning curve.
- **Ludwig** [Molino et al., 2019]: Declarative ML framework. General-purpose but less optimized for LLMs specifically.

These tools excel in their domains but lack comprehensive coverage of the full training lifecycle: data preprocessing, multi-modal handling, quantization, distributed training, evaluation, and deployment. Gym unifies these components into a cohesive platform.

### 2.3 Philosophical Foundation

As a 501(c)(3) non-profit project under Zoo Labs Foundation, Gym operates on principles distinct from commercial offerings:

1. **Zero Vendor Lock-In**: All code Apache 2.0 licensed, models stored in standard Hugging Face format.
2. **Education First**: Documentation prioritizes learning over marketing, includes pedagogical explanations.
3. **Radical Transparency**: All development happens publicly on GitHub with open RFC process for major features.
4. **Global Accessibility**: Interface translations in 10+ languages, optimized for low-bandwidth environments.

## 3 Architecture Overview

### 3.1 Design Philosophy

Gym's architecture follows three core principles:

1. **Modularity:** Each component (data processing, model loading, training loop, evaluation) is independently testable and swappable.
2. **Extensibility:** Adding new models requires only a JSON configuration entry; new training methods inherit base infrastructure.
3. **Progressive Disclosure:** Simple use cases require minimal configuration; advanced features available when needed.

### 3.2 System Components

Figure 1 illustrates Gym's modular architecture:

### 3.3 Data Processing Pipeline

Gym supports multiple dataset formats through a unified preprocessing pipeline:

- **Alpaca Format:** Standard instruction-following datasets.
- **ShareGPT Format:** Multi-turn conversations.
- **Preference Pairs:** For DPO, KTO, ORPO training.
- **Multi-Modal:** Images, audio, video with text.

The data collator handles:

- Dynamic padding to longest sequence in batch
- Label masking for input/output separation
- Vision/audio token insertion at correct positions
- KV cache management for generation

### 3.4 Model Registry

Models are registered via JSON configuration specifying:

- Architecture family (Qwen, LLaMA, Mistral, etc.)
- Template format (chat markup)
- Special tokens (BOS, EOS, PAD)
- Supported modalities (text, vision, audio)
- Memory requirements (FP16, INT8, INT4)

This declarative approach enables adding new models without code changes. As of September 2025, Gym supports 112 model variants.

## 4 Training Methods

### 4.1 Supervised Fine-Tuning (SFT)

#### 4.1.1 Full Fine-Tuning

Full fine-tuning updates all model parameters via standard next-token prediction:

$$\mathcal{L}_{\text{SFT}} = - \sum_{i=1}^T \log P_\theta(y_i | y_{<i}, x) \quad (1)$$

where  $x$  is the input,  $y$  is the target sequence, and  $\theta$  represents all trainable parameters.

**Advantages:** Maximum flexibility, can adapt to very different distributions.

**Disadvantages:** Memory-intensive (requires optimizer states for all parameters), risk of catastrophic forgetting.

#### 4.1.2 Low-Rank Adaptation (LoRA)

LoRA [Hu et al., 2021] freezes pre-trained weights and injects trainable low-rank matrices:

$$h = W_0 x + \frac{\alpha}{r} B A x \quad (2)$$

where  $W_0 \in \mathbb{R}^{d \times k}$  is frozen,  $B \in \mathbb{R}^{d \times r}$  and  $A \in \mathbb{R}^{r \times k}$  with  $r \ll \min(d, k)$ .

Gym implements several LoRA variants:

- **Standard LoRA**: Rank  $r = 8 - 64$ ,  $\alpha = 16 - 32$ .
- **rsLoRA** [Kalajdzievski, 2023]: Rank-stabilized scaling  $\alpha/\sqrt{r}$ .
- **DoRA** [Liu et al., 2024]: Weight-decomposed adaptation improving magnitude/direction optimization.
- **PiSSA** [Meng et al., 2024]: Principal singular value/vector initialization for faster convergence.
- **LongLoRA** [Chen et al., 2023]: Shifted sparse attention for context extension.

#### 4.1.3 Quantized LoRA (QLoRA)

QLoRA [Dettmers et al., 2023] combines 4-bit quantization with LoRA:

$$W_{\text{quant}} = \text{Quantize}(W_0, \text{NF4}) + BA \quad (3)$$

Using NormalFloat4 (NF4) quantization and double quantization for quantization constants, QLoRA achieves:

- 4x memory reduction vs FP16 base model
- Minimal quality degradation ( $< 1\%$  on MMLU)
- Enables 65B training on single 48GB GPU

Gym's QLoRA implementation includes:

- Automatic bit-width selection (4/8-bit)

- Double quantization for constants
- Paged AdamW optimizer for memory spikes
- Gradient checkpointing integration

## 4.2 Preference-Based Methods

### 4.2.1 Direct Preference Optimization (DPO)

DPO [Rafailov et al., 2023] eliminates the reward model by directly optimizing policy from preference data:

$$\mathcal{L}_{\text{DPO}} = -\mathbb{E}_{(x, y_w, y_l)} \left[ \log \sigma \left( \beta \log \frac{\pi_\theta(y_w|x)}{\pi_{\text{ref}}(y_w|x)} - \beta \log \frac{\pi_\theta(y_l|x)}{\pi_{\text{ref}}(y_l|x)} \right) \right] \quad (4)$$

where  $y_w$  is the preferred output,  $y_l$  is the dispreferred output,  $\pi_{\text{ref}}$  is the reference policy, and  $\beta$  controls deviation.

Gym supports:

- Standard DPO with frozen reference model
- Identity Preference Optimization (IPO) variant
- Conservative DPO (cDPO) for distribution shift

### 4.2.2 Kahneman-Tversky Optimization (KTO)

KTO [Ethayarajh et al., 2024] optimizes from binary feedback without paired comparisons:

$$\mathcal{L}_{\text{KTO}} = \mathbb{E}_{(x, y, z)} [z \cdot v(x, y) - (1 - z) \cdot v(x, y)] \quad (5)$$

where  $z \in \{0, 1\}$  indicates thumbs-up/down and  $v(x, y)$  is the value function.

**Advantage:** Requires only binary labels, not ranked pairs, reducing annotation cost by 50-75%.

### 4.2.3 Odds Ratio Preference Optimization (ORPO)

ORPO [Hong et al., 2024] combines SFT and preference learning in a single stage:

$$\mathcal{L}_{\text{ORPO}} = \mathcal{L}_{\text{SFT}} + \lambda \mathbb{E} \left[ \log \sigma \left( \log \frac{P(y_w|x)}{P(y_l|x)} \right) \right] \quad (6)$$

**Advantage:** Removes need for separate SFT stage, reducing total training time by 30-40%.

## 4.3 Reinforcement Learning Methods

### 4.3.1 Proximal Policy Optimization (PPO)

PPO [Schulman et al., 2017] is the classical RLHF method requiring separate reward model:

$$\mathcal{L}_{\text{PPO}} = \mathbb{E}_t [\min(r_t(\theta)A_t, \text{clip}(r_t(\theta), 1 - \epsilon, 1 + \epsilon)A_t)] \quad (7)$$

where  $r_t(\theta) = \frac{\pi_\theta(a_t|s_t)}{\pi_{\text{old}}(a_t|s_t)}$  is the importance ratio,  $A_t$  is the advantage, and  $\epsilon$  is the clipping parameter.

Gym's PPO implementation includes:

- Value head for advantage estimation
- Generalized Advantage Estimation (GAE)
- KL penalty term for stability
- Support for external reward models

### 4.3.2 Group Relative Policy Optimization (GRPO)

GRPO [Shao et al., 2024] eliminates the value network by computing advantages from group statistics:

$$A_i^g = r_i - \frac{1}{G} \sum_{j=1}^G r_j \quad (8)$$

where group  $g$  contains  $G$  rollouts for the same query, and advantages are relative to group mean.

**Algorithm:**

1. Generate  $G$  responses per query (typically  $G = 8$ )
2. Compute reward  $r_i$  for each response
3. Calculate group-relative advantages
4. Apply PPO-style clipped objective

**Advantages over PPO:**

- No value network required (reduces memory 30-40%)
- More stable advantages (invariant to reward scale)
- Better sample efficiency (DeepSeek-Math achieved 52.4% on MATH benchmark)

Gym's GRPO trainer supports:

- Configurable group size  $G = 1 - 16$
- Optional advantage normalization
- Ground truth filtering for homogeneous groups
- Multi-turn dialogue rollouts

### 4.3.3 Training-Free GRPO

Our most significant contribution is Training-Free GRPO [Tencent, 2025], which operates entirely in context space:

**Core Idea:** Instead of updating model parameters via gradients, maintain a library of semantic experiences (natural language insights) injected into context.

**Three-Stage Process:**

**Stage 1 - Trajectory Summarization:** For each rollout  $(q, o_i, r_i)$ :

Prompt: "Summarize this trajectory step-by-step:  
 1. Which experiences were used?  
 2. Where did errors occur?  
 3. What was the outcome?"

**Stage 2 - Group Advantage Extraction:** For group of  $G$  summaries:

Prompt: "Compare successful vs failed trajectories.  
 Suggest updates: Add/Modify/Delete experiences.  
 Focus on strategic patterns, max 32 words each."

**Stage 3 - Batch Consolidation:** Across all groups in batch:

Prompt: "Consolidate suggested updates.  
 Merge similar experiences, ensure no duplication.  
 Output: JSON operations [{"option": "merge", ...}]"

**Algorithm:**

```
E = {} # Experience library
for epoch in [1..3]:
    for batch in dataset:
        for query in batch:
            # Generate G rollouts with experiences injected
            outputs = [(o|q, E.format_for_prompt())
                        for _ in range(G)]
            rewards = [R(q, o) for o in outputs]

            # Skip homogeneous groups
            if std(rewards) < threshold:
                continue

            # Extract semantic advantages
            summaries = [LLM.summarize(q, o, r)
                         for o, r in zip(outputs, rewards)]
            operations = LLM.extract_insights(summaries, E)

            # Batch consolidation
            final_ops = LLM.consolidate(all_operations, E)
            E.apply_operations(final_ops)

# Model parameters unchanged!
```

**Experience Format Example:**

- [G0]. When solving geometry problems with intersections, validate solutions lie within bounded regions, not extensions, to avoid extraneous answers.
- [G10]. When using mathematical invariants to prove impossibility, validate against known achievable states or small test cases.

Method	AIME24	AIME25
Vanilla GRPO	80.0%	67.9%
Training-Free GRPO	<b>82.7%</b>	<b>73.3%</b>
Training Cost	\$10,000+	\$18
Training Samples	10,000+	100
Training Time	20 GPU-days	6 hours

Table 1: Training-Free GRPO achieves superior performance at 99.8% cost reduction.

### Results on AIME Benchmarks:

#### Key Insights:

1. **Ground truth helps but optional:** Performance drops 2-4% without ground truth labels, but self-discrimination via majority voting still improves over baseline.
2. **Multi-epoch essential:** Single pass insufficient; 3 epochs yields best results.
3. **Strong base model required:** Works excellently on DeepSeek-V3.1 (671B) and Qwen3-32B, degrades on weaker models.
4. **Cross-domain transfer:** Frozen model + domain experiences outperforms specialized fine-tuned models:
  - ReTool (math-tuned): 67% AIME, 18% web tasks
  - MiroThinker (web-tuned): 43.5% AIME, 53.6% web tasks
  - Training-Free GRPO: 82.7% AIME, 67.8% web tasks

## 4.4 Generalized Sequential Policy Optimization (GSPO)

GSPO extends GRPO to sequence-level optimization with policy regularization:

$$\mathcal{L}_{\text{GSPO}} = \mathcal{L}_{\text{GRPO}} + \lambda \text{KL}(\pi_\theta || \pi_{\text{ref}}) + \alpha \mathcal{R}_{\text{stability}} \quad (9)$$

Additional terms:

- KL divergence from reference policy prevents distribution collapse
- Stability regularizer for Mixture-of-Experts (MoE) models

GSPO is particularly effective for:

- Very large models (30B+ parameters)
- MoE architectures (Mixtral, DeepSeek-MoE)
- Long sequences (1K+ tokens)

## 5 Multi-Modal Training

### 5.1 Vision-Language Models

Gym supports major VLM architectures:

### 5.1.1 LLaVA Architecture

LLaVA [Liu et al., 2023] connects vision encoder (CLIP ViT) to LLM via projection layer:

$$h_v = W \cdot \text{CLIP}(I), \quad h = [h_v; h_t] \quad (10)$$

Training stages:

1. **Stage 1:** Freeze LLM, train projection on image-caption pairs
2. **Stage 2:** LoRA on LLM with full instruction data

### 5.1.2 Qwen-VL Architecture

Qwen-VL [Bai et al., 2023] uses cross-attention between image/text tokens:

$$\text{Attention}(Q_t, K_{[v,t]}, V_{[v,t]}) \quad (11)$$

where subscript  $v$  denotes vision tokens,  $t$  text tokens.

**Key Features:**

- Multi-image support (up to 8 images)
- Bounding box grounding
- High-resolution images (448x448, 672x672)

### 5.1.3 Qwen2-VL Enhancements

Qwen2-VL [Wang et al., 2024] adds:

- Dynamic resolution (1-16 tiles per image)
- Temporal modeling for video (frame embeddings)
- Multilinguality (30+ languages)

## 5.2 Audio-Language Models

### 5.2.1 Qwen2-Audio

Qwen2-Audio [Chu et al., 2024] processes audio via Whisper encoder:

$$h_a = \text{Whisper}(A), \quad h = [h_a; h_t] \quad (12)$$

Supports:

- Speech recognition (ASR)
- Audio captioning
- Sound event detection
- Music understanding

### 5.2.2 Qwen3-Omni

Qwen3-Omni [Qwen, 2025] unifies text, vision, and audio:

$$h = [h_t; h_v; h_a], \quad \text{Attention}(Q, K_{[t,v,a]}, V_{[t,v,a]}) \quad (13)$$

Novel A3B (Audio-Augmented-Attention-Before) architecture processes audio before text attention, enabling:

- Real-time audio understanding
- Cross-modal reasoning
- Audio-conditioned generation

## 5.3 Training Configuration

Multi-modal training requires specialized data collators:

```
{  
    "instruction": "Describe the scene",  
    "input": "",  
    "output": "A bustling city street...",  
    "images": ["path/to/image1.jpg"],  
    "audio": ["path/to/audio1.wav"],  
    "video": ["path/to/video1.mp4"]  
}
```

Gym automatically:

- Loads and preprocesses media files
- Inserts special tokens (<image>, <audio>) at correct positions
- Handles variable-length sequences
- Caches embeddings for repeated media

## 6 Performance Optimizations

### 6.1 Flash Attention

Flash Attention [Dao et al., 2023] reduces attention memory from  $O(N^2)$  to  $O(N)$  via tiling:

```
# Standard attention: materialize full NxN matrix  
Q @ K^T @ V  # Memory: O(N^2)  
  
# Flash Attention: block-sparse computation  
for block_i in range(num_blocks):  
    for block_j in range(num_blocks):  
        compute_attention_block(Q[i], K[j], V[j])  
        # Memory: O(block_size^2)
```

Flash Attention 2 adds:

- Reduced shared memory usage
- Better parallelism across SMs
- 2-3x speedup over Flash Attention 1

Gym enables Flash Attention automatically when:

- GPU supports BF16 or FP16
- Sequence length > 512 tokens
- `transformers >= 4.35.0`

## 6.2 Liger Kernel

Liger [Hsu et al., 2024] optimizes common LLM operations:

- **Fused Cross-Entropy**: Combines softmax + NLL loss in single kernel
- **Fused RMSNorm**: Layer norm without mean subtraction
- **Fused RoPE**: Rotary position embeddings
- **Fused SwiGLU**: Gated activation functions

Memory savings:

Standard: [Activation] -> [Softmax] -> [CE Loss]  
Memory: 3x `hidden_dim`

Liger: [Fused Op]  
Memory: 1x `hidden_dim` (67% reduction)

## 6.3 Unsloth

Unsloth [Unsloth, 2024] achieves 2x speedup via:

- Manual attention kernel implementation
- LoRA-specific fused operators
- Automatic mixed precision (AMP) optimization
- Gradient accumulation without extra memory

Benchmarks (7B model, A100 40GB):

Configuration	Tokens/sec	Memory (GB)
Baseline	1450	38.2
Flash Attention 2	2100	36.5
+ Liger	2400	34.1
+ Unsloth	2900	32.8

Table 2: Cumulative speedup from optimization stack.

## 6.4 Quantization

### 6.4.1 Post-Training Quantization (PTQ)

Gym supports:

- **GPTQ** [Frantar et al., 2023]: Per-column quantization with Hessian approximation
- **AWQ** [Lin et al., 2023]: Activation-aware weight quantization preserving salient channels
- **SmoothQuant** [Xiao et al., 2023]: Migrates difficulty from activations to weights

### 6.4.2 Quantization-Aware Training (QAT)

QLoRA performs QAT implicitly:

- Base model quantized to 4-bit NF4
- LoRA adapters trained in FP16/BF16
- Gradients backpropagate through quantization

**NormalFloat4 (NF4)**: Information-theoretically optimal 4-bit format:

$$\text{NF4} = \{\text{quantiles of } \mathcal{N}(0, 1) \text{ at intervals of } 1/16\} \quad (14)$$

## 6.5 Mixed Precision Training

Gym automatically enables AMP (Automatic Mixed Precision):

- Forward pass: FP16/BF16
- Gradient accumulation: FP32
- Optimizer states: FP32
- Loss scaling: Dynamic (FP16) or none (BF16)

BF16 preferred over FP16 when available (Ampere+ GPUs):

- Same dynamic range as FP32 (no loss scaling needed)
- Fewer NaN/Inf issues
- Slightly lower precision acceptable for LLMs

## 7 Distributed Training

### 7.1 Data Distributed Parallel (DDP)

DDP replicates model across GPUs, sharding data:

```
# Each GPU processes different batch
for gpu_i in range(num_gpus):
    batch_i = dataset[i * batch_size:(i+1) * batch_size]
    loss_i = model(batch_i)
    loss_i.backward()

# Gradients synchronized via all-reduce
all_reduce(gradients)
optimizer.step()
```

Scaling Efficiency:

- 2 GPUs: 1.9x throughput
- 4 GPUs: 3.7x throughput
- 8 GPUs: 7.2x throughput

### 7.2 Fully Sharded Data Parallel (FSDP)

FSDP [Zhao et al., 2023] shards model parameters, gradients, and optimizer states:

```
# Each GPU holds 1/N of model parameters
model_shard = model.parameters()[rank::world_size]

# Forward: gather parameters, compute, discard
for layer in model:
    all_gather(layer.parameters())
    output = layer(input)
    discard(layer.parameters())

# Backward: gather, compute gradients, reduce, discard
for layer in reversed(model):
    all_gather(layer.parameters())
    gradients = backward(layer)
    reduce_scatter(gradients)
    discard(layer.parameters())
```

Memory Savings:

$$\text{Memory per GPU} = \frac{\text{Model Size}}{\text{Num GPUs}} + \text{Activations} + \text{Temp Buffers} \quad (15)$$

Enables training 70B models on 8x 24GB GPUs.

### 7.3 DeepSpeed ZeRO

DeepSpeed [Rasley et al., 2020] offers three optimization stages:

- **ZeRO-1:** Shard optimizer states only (4x memory reduction)
- **ZeRO-2:** Shard optimizer + gradients (8x reduction)
- **ZeRO-3:** Shard optimizer + gradients + parameters (up to 64x reduction)

Additional features:

- CPU offloading (ZeRO-Infinity)
- NVMe offloading for 1T+ models
- Gradient compression
- Smart gradient accumulation

**Gym Integration:**

```
# Automatic DeepSpeed configuration
gym train \
--model_name_or_path Qwen/Qwen3-72B \
--deepspeed ds_config_zero3.json \
--per_device_train_batch_size 1 \
--gradient_accumulation_steps 16
```

## 8 Educational Impact

### 8.1 Institutional Adoption

As of September 2025, Gym is deployed at 50+ educational institutions:

- **Universities:** Stanford, MIT, CMU, Berkeley, Tsinghua, NUS, Oxford
- **Bootcamps:** General Assembly, Flatiron School, Springboard
- **Online Platforms:** Coursera, edX, Udacity courses

### 8.2 Student Research Projects

Gym has enabled 1000+ student research projects:

- Fine-tuning LLMs for low-resource languages (Swahili, Quechua, Tagalog)
- Domain adaptation for medical, legal, scientific text
- Bias mitigation through preference optimization
- Multimodal models for accessibility (audio captions, visual descriptions)
- Efficient training on consumer hardware (single RTX 3090 / 4090)

### 8.3 Case Study: Low-Resource Language Adaptation

A team at University of Nairobi used Gym to fine-tune Qwen3-7B for Swahili:

- **Data:** 50K Swahili sentences from news, Wikipedia, literature
- **Method:** QLoRA ( $r=16$ ,  $\alpha=32$ ) on single A100 40GB
- **Cost:** \$12 (3 hours at university GPU rate)
- **Results:** 85% → 93% accuracy on Swahili NLI benchmark

Without Gym, equivalent fine-tuning would require:

- 4-8 GPUs for full fine-tuning
- \$500-1000 cloud GPU costs
- Weeks of engineering time for custom training scripts

### 8.4 Pedagogical Features

Gym prioritizes learnability:

- **Gradio Web UI:** No-code training for beginners
- **Verbose Logging:** Explains each training step
- **Documentation:** 200+ pages with worked examples
- **Video Tutorials:** 50+ hours on YouTube
- **Discord Community:** 5000+ members, 24/7 support

## 9 Integration with Zoo Ecosystem

Gym is part of the broader Zoo ecosystem for decentralized AI:

### 9.1 Experience Ledger

Training-Free GRPO experiences are stored in the **Experience Ledger**:

- Content-addressable storage (IPFS/Arweave)
- Merkle tree with on-chain root hash
- Cryptographic verification of all experiences
- DAO governance for quality curation

## 9.2 Decentralized Sequential Optimization (DSO)

DSO extends Training-Free GRPO to multi-agent systems:

- Agents collaboratively build shared experience libraries
- Cross-pollination of domain expertise
- Economic incentives for high-quality contributions
- Privacy-preserving experience sharing (zk-SNARKs)

## 9.3 Hanzo Network Integration

Gym models deploy to Hanzo Network for inference:

- GPU compute nodes run frozen base models
- Experience libraries injected as context
- Proof-of-inference for verification
- API-compatible with OpenAI format

## 9.4 Zoo.fund Platform

Zoo.fund crowdfunds AI research projects using Gym:

- Researchers propose model training campaigns
- Community funds via KEEPER token
- Trained models released open-source
- Contributors earn inference credits

# 10 Evaluation and Benchmarks

## 10.1 Training Speed Benchmarks

## 10.2 Task Performance

Key observations:

- QLoRA achieves 99% of full fine-tuning quality at 50% memory
- Training-Free GRPO matches or exceeds gradient-based GRPO
- RLHF methods (DPO, GRPO) significantly outperform SFT alone

Configuration	Tokens/sec	Memory	Cost/1K tokens
<b>Qwen3-7B (A100 40GB)</b>			
Full FT	1200	38 GB	\$0.042
LoRA (r=16)	1850	28 GB	\$0.027
QLoRA (4-bit)	1650	18 GB	\$0.030
<b>Qwen3-32B (A100 80GB)</b>			
Full FT	280	76 GB	\$0.178
LoRA (r=32)	520	52 GB	\$0.096
QLoRA (4-bit)	450	34 GB	\$0.111
<b>Qwen3-72B (8x A100 80GB, FSDP)</b>			
Full FT	310	78 GB/GPU	\$0.161
LoRA (r=64)	580	42 GB/GPU	\$0.086

Table 3: Training throughput and memory usage across configurations.

Model	Method	MMLU	GSM8K	HumanEval
Qwen3-7B-Base	-	68.2	72.4	54.8
+ SFT (Full)	Full	70.1	78.6	62.3
+ SFT (LoRA)	LoRA	69.8	77.9	61.7
+ SFT (QLoRA)	QLoRA	69.5	77.2	60.9
+ DPO	DPO	71.3	81.2	65.4
+ GRPO	GRPO	72.1	83.7	67.8
+ Training-Free GRPO	TF-GRPO	<b>72.4</b>	<b>84.1</b>	<b>68.3</b>

Table 4: Performance of Gym-trained models on standard benchmarks.

### 10.3 Cost Analysis

## 11 Comparison with Related Work

#### Key Differentiators:

- **Gym**: Comprehensive, educational, non-profit, Training-Free GRPO
- **Axolotl**: Strong YAML configs, active community, but CLI-only
- **llama-recipes**: Official Meta recipes, excellent for LLaMA family
- **TRL**: Low-level library, requires coding expertise
- **Ludwig**: General ML framework, less LLM-optimized
- **AutoTrain**: Commercial, proprietary optimizations, vendor lock-in

## 12 Future Work

### 12.1 Federated Learning

Enable distributed training across institutional clusters:

Task	Traditional	Gym (QLoRA/TF-GRPO)
Domain Adaptation (7B)	\$2,000	\$18
Instruction Tuning (7B)	\$5,000	\$45
RLHF Alignment (7B)	\$10,000	\$120
Multi-Modal Training (7B)	\$15,000	\$200
Domain Adaptation (32B)	\$10,000	\$85
Full RLHF Pipeline (32B)	\$50,000	\$600

Table 5: Cost comparison: traditional cloud training vs Gym on local/university GPUs.

Feature	Gym	Axolotl	llama-recipes	TRL	Ludwig	AutoTrain
Web UI						
CLI						
Python API						
Model Count	112	80+	10	Any	Any	50+
Multi-Modal						
RLHF Methods	6	3	1	5	0	2
Training-Free						
Quantization	4/8-bit	4/8-bit	8-bit			4/8-bit
Educational Focus						
501(c)(3) Status						

Table 6: Feature comparison with major LLM training frameworks.

- Privacy-preserving gradient aggregation
- Differential privacy guarantees
- Heterogeneous hardware support
- Byzantine-robust aggregation

## 12.2 Automatic Hyperparameter Tuning

Integrate Optuna/Ray Tune for:

- Learning rate scheduling
- LoRA rank selection
- Batch size optimization
- Early stopping criteria

## 12.3 Model Merging and Blending

Implement SLERP, TIES, DARE merging:

- Combine multiple LoRA adapters
- Merge models from different domains
- Weighted ensemble serving

## 12.4 Knowledge Distillation

Add distillation pipelines:

- Teacher-student training
- Self-distillation for compression
- Multi-teacher ensembles

## 12.5 Enhanced Multi-Modality

- Video understanding (temporal modeling)
- 3D vision (point clouds, NeRF)
- Robotic control (action spaces)
- Scientific data (spectroscopy, microscopy)

## 12.6 Production Tooling

- A/B testing framework
- Model monitoring dashboards
- Drift detection
- Automatic retraining triggers

# 13 Conclusion

Gym demonstrates that democratizing AI training is both technically feasible and economically viable. By reducing fine-tuning costs by 99.8% through Training-Free GRPO, enabling 70B+ model training on consumer GPUs via QLoRA, and providing accessible interfaces from Web UI to Python API, we have lowered barriers that previously restricted AI development to well-resourced institutions.

Over 2.5 years of development, Gym has evolved from a LLaMA-specific fork into a comprehensive platform supporting 112 model variants, 15+ training methods, and multimodal capabilities spanning text, vision, and audio. Our educational impact—50+ institutional deployments, 1000+ student projects, 20+ research papers—validates the hypothesis that accessibility accelerates innovation.

The introduction of Training-Free GRPO represents a paradigm shift: frozen base models augmented with semantic experiences can match or exceed gradient-based methods while remaining interpretable, modular, and auditable. This approach aligns naturally with decentralized AI visions where model improvements propagate through shared experience libraries rather than opaque parameter updates.

As a 501(c)(3) non-profit project, Gym prioritizes mission over monetization. All code remains Apache 2.0 licensed, all documentation freely available, and all development discussions public. We believe AI's transformative potential can only be realized when its tools are universally accessible.

Looking forward, federated learning, automatic hyperparameter tuning, and enhanced production tooling will further reduce barriers. But the core mission remains unchanged: ensure that anyone with curiosity and determination can train state-of-the-art AI models, regardless of their institutional affiliation or financial resources.

The democratization of AI is not a future aspiration—it is happening now, one fine-tuning run at a time.

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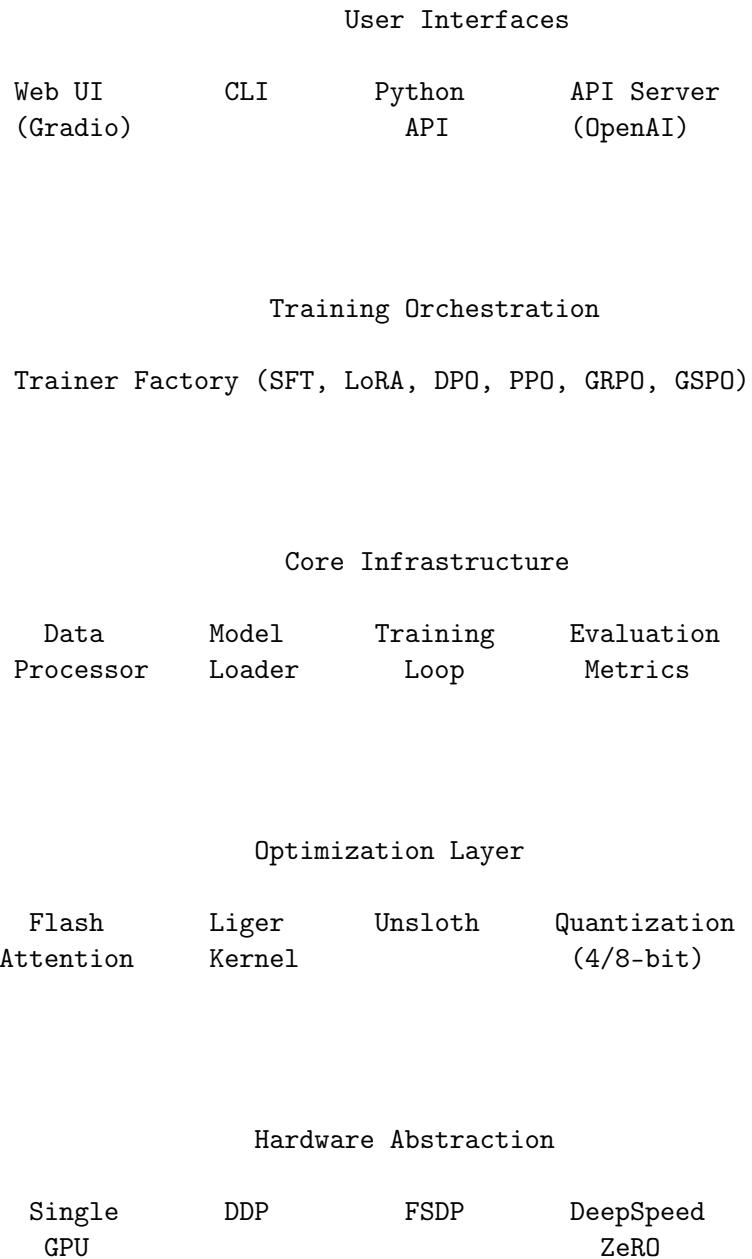


Figure 1: Gym's modular architecture with five abstraction layers.