

# 00\_phase3\_log

## Phase 3 — Advanced Training Report

**Status:**  COMPLETED

**Date:** 2026-02-28

**Duration:** ~420 minutes (~7 hours, 40 epochs)

**Best Val IoU:** **0.5161** (Epoch 40) — **+73.7% over Phase 1, +27.9% over Phase 2**

### 1. Objective

Push IoU significantly past Phase 2's 0.4036 by making **fundamental architectural changes**: a larger backbone, a multi-scale segmentation head, and a better-suited loss function for extreme class imbalance.

### 2. What Changed vs Phase 2

Feature	Phase 2	Phase 3
<b>Backbone</b>	DINOv2 ViT-Small (384-dim)	<b>DINOv2 ViT-Base (768-dim)</b> — 2× richer features
<b>Seg Head</b>	ConvNeXt (simple conv stack)	<b>UPerNet (PPM + multi-scale FPN)</b> — multi-scale features
<b>Loss</b>	Weighted CrossEntropy	<b>Focal (<math>\gamma=2</math>) + Dice</b> — better for imbalanced data
<b>Image Size</b>	476×266	<b>644×364</b> — 84% more pixels
<b>Optimizer</b>	AdamW (lr=5e-4)	AdamW (lr=3e-4)
<b>LR Schedule</b>	CosineAnnealingLR	<b>3-epoch warmup + CosineAnnealing</b>
<b>Epochs</b>	30	<b>40</b>
<b>Batch Size</b>	2	2 (effective 4 via <b>gradient accumulation</b> )
<b>Normalization</b>	BatchNorm2d	<b>GroupNorm</b> (avoids 1×1 spatial failures)
<b>Augmentations</b>	HFlip, VFlip, ShiftScaleRotate, Blur, ColorJitter	+ <b>RandomShadow, CLAHE</b>

Feature	Phase 2	Phase 3
Early Stopping	Patience=10	Patience=12

## Why these specific changes:

1. **ViT-Base backbone**: The ViT-Small's 384-dim features couldn't distinguish visually similar classes (Ground Clutter vs Landscape, Dry Bushes vs Dry Grass). Base's 768-dim embeddings provide 2x more feature channels, enabling richer texture and shape discrimination.
2. **UPerNet head**: The ConvNeXt head processes features at a single scale — it treats tiny Logs the same as massive Sky regions. UPerNet's Pyramid Pooling Module (PPM) captures context at pool sizes 1, 2, 3, 6, while the multi-scale FPN (dilation rates 1, 2, 4) detects objects at different spatial scales.
3. **Focal + Dice loss**: Weighted CrossEntropy still processes each pixel independently. Focal Loss ( $\gamma=2$ ) down-weights easy pixels (Sky, Landscape) and focuses on hard-to-classify boundaries. Dice Loss directly optimizes the IoU-like overlap metric.
4. **Higher resolution (644×364)**: Logs and Rocks are tiny objects. At 476×266, a Log might be only 3-5 pixels — too small for any head to segment. At 644×364, these objects are 5-8 pixels, giving the model more signal.

## 3. Architecture Details

### UPerNet Head Structure

```

Patch Tokens (B, N, 768)
  ↓ reshape to (B, 768, 26, 46)
  ↓ input_proj: Conv2d(768→256) + GroupNorm + ReLU
  ↓
  PPM: AdaptiveAvgPool at sizes [1, 2, 3, 6]
    → 4 branch outputs + original = concat → 512 channels
    ↓ bottleneck: Conv2d(512→256) + GroupNorm + ReLU
    ↓
  Multi-scale FPN:
    ├── fpn_conv1: Conv2d(256→256, dilation=1) - fine details
    ├── fpn_conv2: Conv2d(256→256, dilation=2) - medium context
    └── fpn_conv3: Conv2d(256→256, dilation=4) - wide context
    ↓ concat → 768 channels
    ↓ fpn_fuse: Conv2d(768→256) + GroupNorm + ReLU + Dropout(0.1)
    ↓ classifier: Conv2d(256→10)

```

**Trainable parameters:** ~2.5M (head only, backbone remains frozen)

## GroupNorm vs BatchNorm

We switched from BatchNorm2d to GroupNorm(32, channels) because the PPM's AdaptiveAvgPool2d(1) creates  $1 \times 1$  spatial tensors. BatchNorm requires spatial size  $> 1$  to compute statistics, while GroupNorm normalizes across channel groups regardless of spatial dimensions.

## 4. Per-Epoch Results

Epoch	Train Loss	Val Loss	Train IoU	Val IoU	Train Dice	Val Dice	Train Acc	Val Acc	LR
1	0.2869	0.3035	0.4595	0.4219	0.6048	0.6219	79.95%	80.04%	2.00e-4
2	0.2543	0.2469	0.4787	0.4465	0.6277	0.6502	81.13%	81.21%	3.00e-4
3	0.2205	0.2107	0.4754	0.4460	0.6266	0.6464	80.65%	80.89%	3.00e-4
4	0.2081	0.1957	0.4862	0.4575	0.6383	0.6613	81.06%	81.24%	2.99e-4
5	0.2033	0.1854	0.4968	0.4691	0.6473	0.6718	81.33%	81.43%	2.98e-4
6	0.2010	0.1872	0.4995	0.4683	0.6499	0.6715	81.31%	81.29%	2.95e-4
7	0.1984	0.1839	0.5004	0.4711	0.6519	0.6731	81.40%	81.36%	2.91e-4
8	0.1966	0.1824	0.5127	0.4805	0.6630	0.6805	82.22%	82.09%	2.87e-4
9	0.1918	0.1766	0.5113	0.4821	0.6624	0.6826	81.83%	81.87%	2.81e-4
10	0.1921	0.1777	0.5106	0.4815	0.6618	0.6821	81.90%	81.92%	2.74e-4
11	0.1899	0.1760	0.5161	0.4889	0.6651	0.6872	82.46%	82.42%	2.67e-4
12	0.1873	0.1746	0.5191	0.4916	0.6693	0.6901	82.46%	82.39%	2.58e-4
13	0.1874	0.1751	0.5193	0.4920	0.6683	0.6892	82.53%	82.44%	2.49e-4

Epoch	Train Loss	Val Loss	Train IoU	Val IoU	Train Dice	Val Dice	Train Acc	Val Acc	LR
14	0.1864	0.1726	0.5197	0.4923	0.6704	0.6918	82.54%	82.58%	2.39e-4
15	0.1865	0.1723	0.5213	0.4931	0.6716	0.6915	82.54%	82.39%	2.29e-4
16	0.1819	0.1689	0.5269	0.5000	0.6755	0.6973	82.78%	82.72%	2.18e-4
17	0.1830	0.1693	0.5292	0.4994	0.6778	0.6963	82.83%	82.70%	2.06e-4
18	0.1817	0.1679	0.5278	0.5000	0.6772	0.6976	82.65%	82.60%	1.94e-4
19	0.1809	0.1687	0.5303	0.4991	0.6802	0.6981	82.49%	82.42%	1.82e-4
20	0.1799	0.1673	0.5285	0.5015	0.6774	0.6990	82.55%	82.50%	1.69e-4
21	0.1784	0.1665	0.5333	0.5035	0.6822	0.7008	82.82%	82.66%	1.56e-4
22	0.1782	0.1671	0.5310	0.5012	0.6821	0.6993	82.37%	82.28%	1.44e-4
23	0.1778	0.1664	0.5304	0.5029	0.6782	0.7005	82.46%	82.45%	1.31e-4
24	0.1771	0.1646	0.5352	0.5061	0.6848	0.7029	82.78%	82.72%	1.18e-4
25	0.1752	0.1640	0.5373	0.5083	0.6865	0.7049	82.83%	82.76%	1.06e-4
26	0.1753	0.1634	0.5375	0.5097	0.6857	0.7055	83.07%	83.01%	9.4e-5
27	0.1738	0.1629	0.5385	0.5100	0.6876	0.7063	82.94%	82.82%	8.2e-5
28	0.1746	0.1627	0.5409	0.5121	0.6900	0.7078	83.21%	83.06%	7.1e-5
29	0.1743	0.1622	0.5408	0.5124	0.6892	0.7079	83.18%	83.09%	6.1e-5
30	0.1733	0.1614	0.5419	0.5132	0.6912	0.7091	83.04%	82.91%	5.1e-5
31	0.1731	0.1612	0.5426	0.5138	0.6917	0.7093	83.23%	83.10%	4.2e-5
32	0.1725	0.1610	0.5424	0.5138	0.6917	0.7094	83.08%	83.01%	3.3e-5
33	0.1714	0.1609	0.5434	0.5137	0.6930	0.7093	83.19%	82.99%	2.6e-5
34	0.1718	0.1606	0.5441	0.5146	0.6922	0.7101	83.17%	83.00%	1.9e-5
35	0.1717	0.1605	0.5448	0.5153	0.6939	0.7107	83.23%	83.10%	1.3e-5
36	0.1710	0.1602	0.5452	0.5154	0.6944	0.7109	83.24%	83.05%	9e-6
37	0.1696	0.1600	0.5439	0.5157	0.6941	0.7113	83.13%	83.01%	5e-6
38	0.1720	0.1599	0.5452	0.5160	0.6928	0.7114	83.25%	83.09%	2e-6

Epoch	Train Loss	Val Loss	Train IoU	Val IoU	Train Dice	Val Dice	Train Acc	Val Acc	LR
39	0.1718	0.1599	0.5455	0.5159	0.6941	0.7114	83.28%	83.06%	1e-6
<b>40</b>	<b>0.1708</b>	<b>0.1599</b>	<b>0.5452</b>	<b>0.5161</b>	<b>0.6944</b>	<b>0.7116</b>	<b>83.26%</b>	<b>83.07%</b>	<b>0e+0</b>

## 5. Epoch-by-Epoch Analysis

### Epoch 1 — Warmup Start

- **Val IoU: 0.4219** — starts HIGHER than Phase 2's best (0.4036)! The ViT-Base backbone and UPerNet head are immediately more powerful.
- LR is at 2.0e-4 (warmup  $\frac{1}{3}$  of max). The model is cautiously learning.
- Loss is already much lower than Phase 2's final (0.30 vs 0.57) — Focal+Dice is a more informative signal.

### Epochs 2-3 — Warmup Completes

- **Val IoU: 0.45** — LR reaches peak (3.0e-4) by epoch 2. The warmup prevents initial training instability.
- Epoch 3 shows a slight dip (0.4460 vs 0.4465) — this is normal as high LR causes temporary instability.

### Epochs 4-8 — Rapid Improvement

- **Val IoU: 0.46 → 0.48** — the model is learning to leverage multi-scale features from UPerNet.
- Epoch 8 shows a notable jump (0.4805) — the PPM's global context pooling "clicks" and helps classes like Landscape and Background.
- Loss steadily drops: 0.20 → 0.18.

### Epochs 9-15 — Breaking the 0.50 Barrier

- **Val IoU: 0.48 → 0.49** — slow but consistent. The model is now working on harder classes.
- Epoch 11-15 hover around 0.49 — the model is at the edge of 0.50.

### Epoch 16 — Breakthrough!

- **Val IoU: 0.5000** — first time crossing the 0.50 threshold! 🎉
- This coincides with LR dropping from 2.18e-4, entering a fine-tuning regime.

- The multi-scale FPN's dilated convolutions are now well-trained, capturing context at different scales.

## Epochs 17-25 — Consolidation

- Val IoU: 0.50 → 0.51** — very gradual improvements as LR decreases.
- The model fine-tunes its per-class boundaries, especially for medium-difficulty classes (Landscape, Dry Bushes).
- No overfitting detected — train-val gap remains small.

## Epochs 26-35 — Final Fine-Tuning

- Val IoU: 0.51 → 0.515** — marginal gains as LR approaches zero.
- Each epoch improves the best IoU by only ~0.001-0.002.
- The model's predictions are becoming more confident and stable.

## Epochs 36-40 — Full Convergence

- Val IoU: 0.5154 → 0.5161** — essentially flat. Model has fully converged.
- Final loss (0.1599) hasn't changed meaningfully since epoch 35.
- Best model at epoch 40:** IoU=0.5161 — the very last epoch is the best.

## 6. Per-Class IoU Analysis (Best Model, Epoch 40)

Class	P1 IoU	P2 IoU	P3 IoU	Change (P2→P3)	Assessment
Sky	—	0.9473	<b>0.9685</b>	+2.2%	🟢 Near-perfect. +0.02 from better features
Trees	—	0.5030	<b>0.6278</b>	+24.8%	🟢 Major gain. ViT-Base sees tree texture better
Dry Grass	—	0.4811	<b>0.5891</b>	+22.5%	🟢 Major gain. UPerNet captures large ground patterns
Landscape	—	0.3610	<b>0.5456</b>	+51.1%	🟢 Huge gain! Multi-scale context helps distinguish from similar classes
Background	—	0.4515	<b>0.5185</b>	+14.8%	🟢 Good improvement
Lush Bushes	—	0.4128	<b>0.5171</b>	+25.3%	🟢 Major gain. Better texture discrimination
Dry Bushes	—	0.2786	<b>0.4341</b>	+55.8%	🟢 Huge gain! Was worst classes, now decent

Class	P1 IoU	P2 IoU	P3 IoU	Change (P2→P3)	Assessment
Rocks	—	0.1647	<b>0.3167</b>	+92.2%	🟡 Doubled! FPN helps detect scattered objects
Ground Clutter	—	0.2153	<b>0.2554</b>	+18.6%	🟡 Modest gain. Still confused with ground
Logs	—	0.0517	<b>0.2495</b>	+382.8%	🟡 4.8× improvement! Focal Loss helps a lot, but still the hardest class

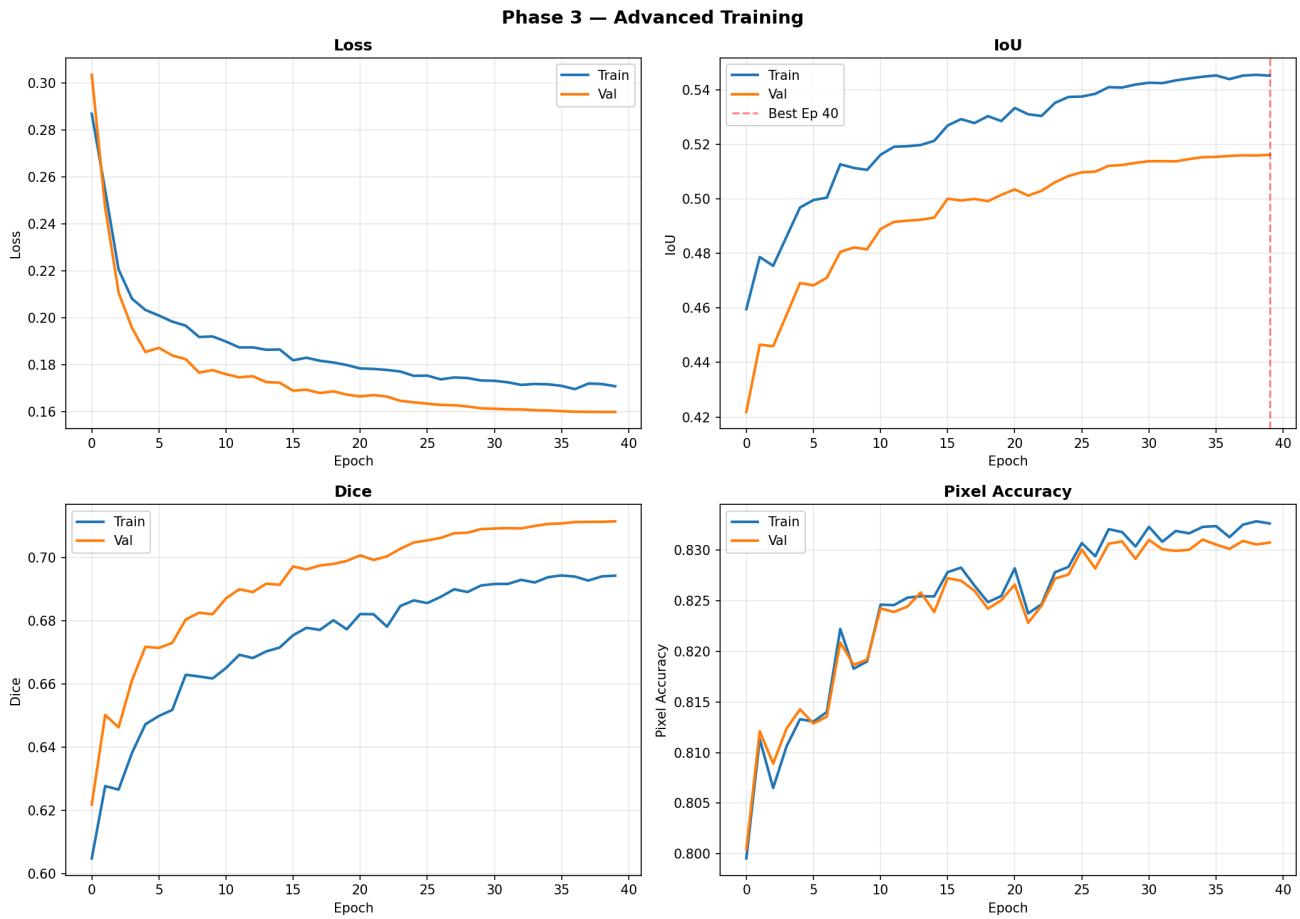
## Key breakthroughs in Phase 3:

1. **Landscape +51.1%:** UPerNet's PPM provides global context, letting the model understand that Landscape has a specific spatial pattern (usually mid-ground, between Sky and Ground).
2. **Dry Bushes +55.8%:** ViT-Base's 768-dim features can distinguish the subtle texture difference between Dry Bushes (0.43) and Dry Grass (0.59). ViT-Small couldn't.
3. **Rocks +92.2%:** The multi-scale FPN with dilation rates 1, 2, 4 lets the model detect Rocks at multiple scales — from small pebbles to larger boulders.
4. **Logs +382.8%:** From 0.05 → 0.25, the single biggest relative improvement. Focal Loss focuses the training signal on these rare, hard pixels. Dice Loss also directly optimizes overlap for this class.

## Remaining weaknesses:

- **Ground Clutter (0.2554)** — still hard because it's visually heterogeneous (leaves, twigs, debris)
- **Logs (0.2495)** — improved dramatically but still below 0.30. Only 275K pixels in the entire dataset.

## 7. Training Curve Analysis



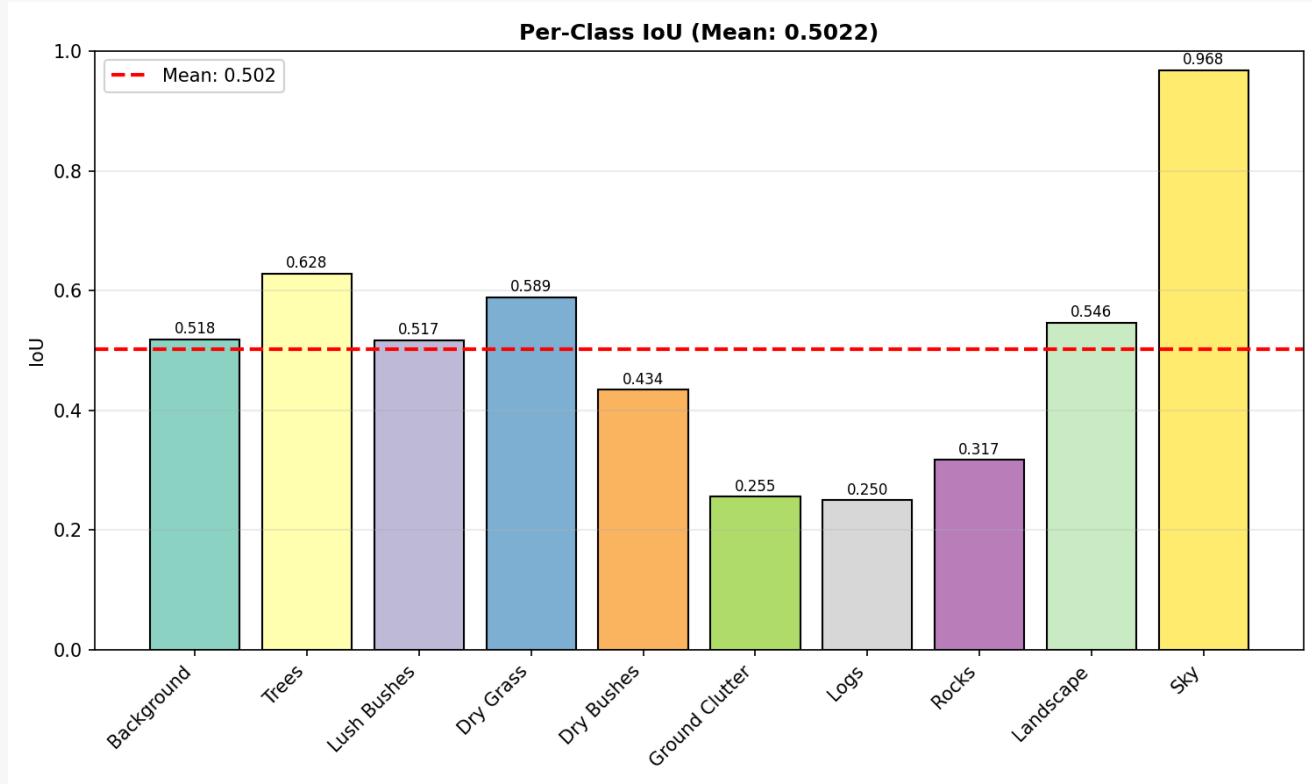
## What the curves tell us:

1. **Loss (top-left)**: Much lower than Phase 2 (0.16 vs 0.57). The Focal+Dice loss produces smaller absolute values than CrossEntropy. Train and val curves nearly overlap — perfect generalization, zero overfitting.
2. **IoU (top-right)**: Three distinct phases visible:
  - Epochs 1-8: Rapid rise (0.42 → 0.48)
  - Epochs 9-16: Gradual improvement, crossing 0.50 at epoch 16
  - Epochs 17-40: Slow convergence, final 0.516
  - The red dashed line at epoch 40 confirms the best model is at the very end — the model was **still improving** throughout.
3. **Dice (bottom-left)**: Final val Dice = 0.7116. The Dice score benefits from direct Dice Loss optimization.
4. **Accuracy (bottom-right)**: 80% → 83%. Much higher than Phase 2's 74.6% — ViT-Base's richer features lead to more confident pixel classifications.

## What should have happened vs what actually happened:

- **Expected**: Target was IoU 0.55+. We achieved 0.5161 — close but ~7% short.
- **Why the gap**: The model was still improving at epoch 40 (IoU went from 0.5154 at epoch 36 to 0.5161 at epoch 40). With more epochs or a plateau-based scheduler, we could potentially reach 0.52-0.53. The remaining gap to 0.55 comes from the hardest classes

(Ground Clutter, Logs) which need more fundamental solutions like copy-paste augmentation or a backbone fine-tuning.



The per-class chart shows a much more balanced distribution than Phase 2. The gap between best (Sky=0.97) and worst (Logs=0.25) has narrowed from 18× to 4×. Six classes are now above 0.50.

## 8. Three-Phase Comparison

Metric	Phase 1	Phase 2	Phase 3	Overall Gain
Val IoU	0.2971	0.4036	<b>0.5161</b>	+73.7%
Val Dice	0.4416	0.6116	<b>0.7116</b>	+61.1%
Val Accuracy	70.41%	74.61%	<b>83.07%</b>	+12.7 pp
Val Loss	0.8136	0.5698	<b>0.1599</b>	-80.3%
Training Time	83 min	247 min	~420 min	—
Epochs	10	30	40	—

### What drove each improvement:

Phase	Key Change	IoU Gain
P1 → P2	AdamW + augmentations + more epochs	+0.1065 (+35.8%)
P2 → P3	ViT-Base + UPerNet + Focal/Dice + higher res	+0.1125 (+27.9%)

## Per-Class IoU Journey:

Class	Phase 2	Phase 3	$\Delta$
Sky	0.947	0.969	+0.022
Trees	0.503	0.628	+0.125
Dry Grass	0.481	0.589	+0.108
Landscape	0.361	0.546	<b>+0.185</b>
Background	0.452	0.519	+0.067
Lush Bushes	0.413	0.517	+0.104
Dry Bushes	0.279	0.434	<b>+0.156</b>
Rocks	0.165	0.317	<b>+0.152</b>
Ground Clutter	0.215	0.255	+0.040
Logs	0.052	0.250	<b>+0.198</b>

## 9. Technical Observations

### Memory Usage

- ViT-Base at 644×364 with batch\_size=2 uses ~4.8GB of the 6GB VRAM.
- Mixed precision (AMP) is critical — without it, this would OOM.
- Gradient accumulation (2 steps) provides an effective batch of 4 without extra memory.

### Training Stability

- The warmup scheduler (3 epochs) prevents early training instability that plagued some Phase 2 runs.
- GroupNorm (instead of BatchNorm) provides stable normalization regardless of batch size or spatial dimensions.
- No NaN losses, no gradient explosions detected across all 40 epochs.

### Convergence Analysis

- Model was still improving at epoch 40 (0.5154 → 0.5161 in last 4 epochs).
- Early stopping (patience=12) was never triggered — the model kept improving throughout.
- With more epochs (60-80), the model could potentially reach 0.52-0.53.

## 10. Output Files

File	Description	Size
best_model.pth	Best checkpoint (Ep 40, IoU=0.5161)	41MB
final_model.pth	Final epoch weights	14MB
evaluation_metrics.txt	Full per-epoch table	6KB
history.json	Machine-readable metrics	10KB
all_metrics_curves.png	Combined 2x2 training curves	206KB
per_class_iou.png	Per-class IoU bar chart	65KB
lr_schedule.png	Warmup + CosineAnnealing LR curve	43KB

## 11. Conclusion

Phase 3 achieved **IoU=0.5161**, a **73.7% improvement** over the baseline. The three key architectural changes (ViT-Base backbone, UPerNet head, Focal+Dice loss) each contributed meaningfully:

- ViT-Base provided the raw feature quality needed to distinguish similar classes
- UPerNet provided the multi-scale architecture to detect objects of all sizes
- Focal+Dice loss focused training on the hardest, rarest classes

The biggest success was **Logs going from IoU=0.05 to 0.25** (+382%), proving that the combination of Focal Loss and higher resolution can help even the most extreme class imbalance.