

Research and Implementation of Multi-Dataset Training for Image Classification with Discrepant Taxonomies

Master Thesis Presentation

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Outline

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- 2 Method Overview
- 3 Relationship Selection Methods
- 4 Synthetic Ground Truth
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The Challenge: Limited Scope of Traditional Models

- Traditional image classification models are trained on specific datasets
- Each model recognizes only a predefined set of categories
- Multiple models needed for different domains = inefficient storage and deployment

Current Approaches:

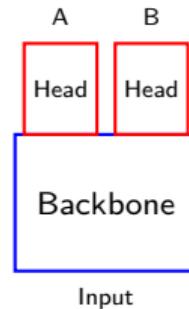
- **Transfer Learning:** Adapt pre-trained models to new tasks
- **Multi-head Architecture:** Shared backbone + task-specific heads
- **Multi-task Learning:** Train on multiple tasks simultaneously

Problem: Still requires separate models or heads for each domain

Our Idea: Universal Model vs. Multi-Head

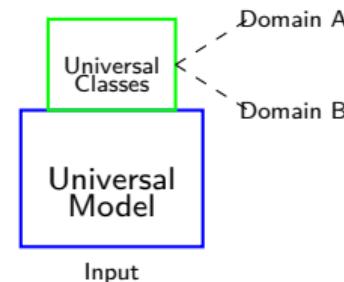
Multi-Head Approach

- Shared backbone
- Task-specific heads
- Automatic feature distillation
- Domain alignment challenges



Universal Model Approach

- Single shared model
- Universal output layer
- Predefined concept mapping
- Static domain conversion

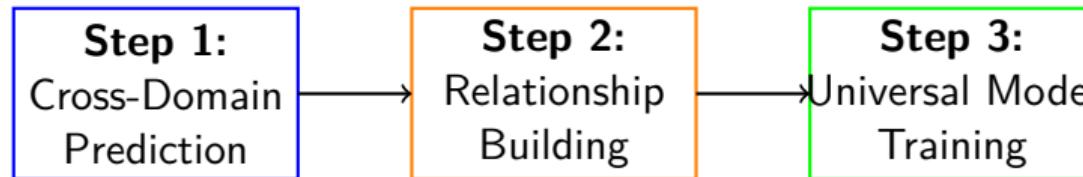


Key Insight: Build explicit concept-to-domain mappings to train a single universal model

Changes to Method of Bevandic et al.

- ① **Weighted Relationships:** Instead of binary, unweighted relationships, we use weighted relationships to capture the strength of associations between classes.
- ② **Relationship Selection Methods:** We try multiple methods to select the most relevant relationships from noisy cross-domain predictions.
- ③ **Synthetic Ground Truth:** We develop a synthetic ground truth generation method to be able to evaluate relationship selection methods in a controlled manner.
- ④ **Discrete Probability Loss Function:** We use a loss function that allows training with probability distributions as targets, enabling the model to learn from the uncertainty in class relationships.

Our Method in 3 Steps



- ① **Cross-Domain Prediction:** Train domain-specific models, run inference on other domains
- ② **Relationship Building:** Extract meaningful relationships from cross-domain predictions and create universal taxonomy
- ③ **Universal Model Training:** Create and train a single model using universal taxonomy

Cross-Domain Prediction Process

Goal: Discover relationships between classes from different datasets

Process:

- ① Train domain-specific models
- ② Run each model on images from *all other* domains, building prediction matrices $M_{ab}(i, j)$
= number of times class c_i^a predicted as class c_j^b
- ③ Create probability matrices $P_{ab}(i, j) = \text{probability of classifying class } c_i^a \text{ as class } c_j^b$

$$P_{ab}(i, j) = \frac{M_{ab}(i, j)}{\sum_{k=1}^{|C_a|} M_{ab}(i, k)} \quad (1)$$

Example: Caltech-256 class "car" predicated by CIFAR-100 model as "automobile" (80%),
"truck" (18%), "butterfly" (2%)

Challenge: Selecting Relevant Relationships

Problems with raw probability matrices:

- Noisy predictions from imperfect models
- Unknown number of true relationships
- Different datasets have different scales of similarity

Solution: Develop multiple relationship selection methods and evaluate them using a synthetic ground truth with custom metrics

Relationship Selection Methods Explained

① Most Common Foreign Prediction (MCFP) by Bevandic et al.:

$$\text{select_relationships}(P_{ab}) = \{(i, j) \mid j = \operatorname{argmax}_{j'} P_{ab}(i, j')\} \quad (2)$$

② Naive Thresholding:

$$\text{select_relationships}(P_{ab}) = \{(i, j) \mid P_{ab}(i, j) \geq t\} \quad (3)$$

③ Density Thresholding: Select minimum relationships covering $p\%$ of probability mass

④ Relationship Hypothesis: Assumes relationships based on shared concepts should have equal probabilities. For each class, find optimal k relationships by minimizing:

$$\sum_{j=1}^k \left| X_i(j) - \frac{1}{k} \right| + \sum_{j=k+1}^{|C_b|} X_i(j) \quad (4)$$

where $X_i(j)$ are sorted probabilities in descending order.

The Need for Controlled Ground Truth

Problem: Real datasets lack clear inter-dataset relationships

- **Manual:** Time-consuming, subjective
- **WordNet:** Text-based relationships don't match visual similarities
- **Known taxonomies:** Do not represent our complex use case

Solution: Merge classes from a single dataset into different variants with controlled relationships

Example:

- We have classes "car", "eye", "dog", "butterfly"
- Create Domain A: "{car, eye}", "{butterfly}"
- Create Domain B: "{car, butterfly}", "{dog, eye}"
- "A:{car, eye}" → "B:{car, butterfly}" (50%)
- "A:{butterfly}" → "B:{car, butterfly}" (100%)

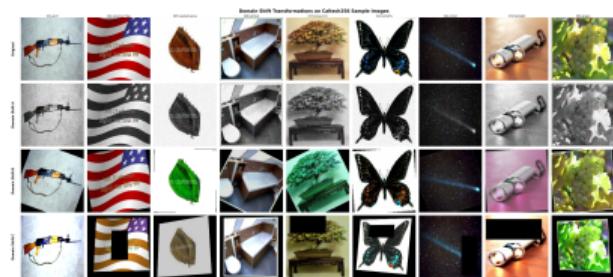
Domain-Shifted Synthetic Datasets

Problem: Original synthetic variants too easy (same underlying images)

Solution: Apply domain transformations to create realistic challenges

Transformations Applied:

- **Domain A:** Noisy grayscale
- **Domain B:** Rotation + blur
- **Domain C:** Random erasing + color jitter + perspective shifts



Results:

- Model accuracy drops by 10%
- More realistic cross-domain predictions
- Better evaluation of relationship selection methods

Example images from domain-shifted variants

Evaluation Metrics for Relationship Selection

How do we measure the quality of selected relationships?

- ① **Edge Difference Ratio (EDR)**: Measures difference in edge weights between predicted and ground truth graphs

$$\text{EDR}(G_1, G_2) = \frac{\sum_{i,j} |A_1(i,j) - A_2(i,j)|}{\sum_{i,j} \max(A_1(i,j), A_2(i,j))} \quad (5)$$

Range: [0,1], where 0 = identical graphs, 1 = no common edges

- ② **Precision & Recall**: Binary evaluation of relationship presence

- Convert adjacency matrices to binary: $B(i,j) = 1$ if $A(i,j) > 0$
- **Precision** = $\frac{TP}{TP+FP}$ (correctness of selected relationships)
- **Recall** = $\frac{TP}{TP+FN}$ (coverage of true relationships)
- **F1 Score** = Harmonic mean of precision and recall

Relationship Selection Results: Domain-Shifted Evaluation

Evaluation on domain-shifted synthetic datasets (more realistic)

Method	Parameter	EDR	Precision	Recall	F1 Score
Relationship Hypothesis	5	0.759	0.390	0.543	0.444
Naive Thresholding	0.10	0.761	0.418	0.519	0.450
Density Thresholding	0.60	0.766	0.349	0.582	0.426
MCFP	N/A	0.842	0.490	0.226	0.305

Table: Performance on domain-shifted synthetic datasets (Caltech-101, Caltech-256, CIFAR-100) with globally optimal parameters

Key Observations:

- **Relationship Hypothesis** achieves best EDR 0.759
- **MCFP** maintains highest precision but lowest recall
- Maybe still not realistic enough, but suitable for getting method parameters

Universal Taxonomy Building Rules

How do we convert relationship graphs into universal taxonomies?

① Isolated Node Rule: Classes with no relationships

- Create new universal class for standalone domain classes
- Ensures all classes are represented in universal taxonomy

② Bidirectional Relationship Rule: Classes with mutual relationships ($A \leftrightarrow B$)

- Create single universal class C with relationships $A \rightarrow C$, $B \rightarrow C$
- Indicates classes likely represent the same concept

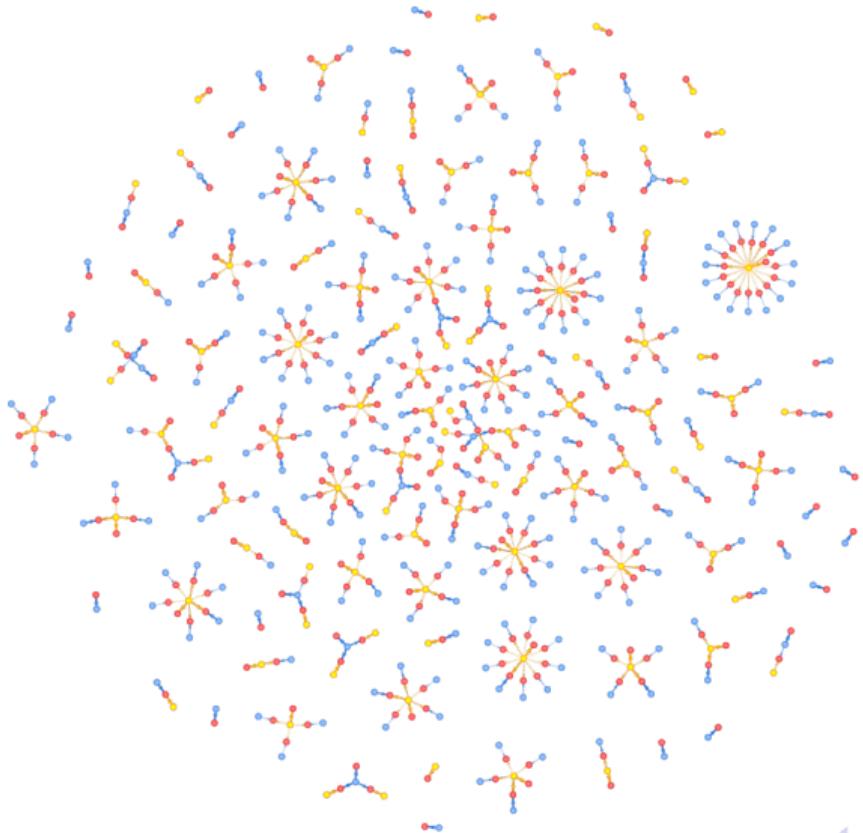
③ Transitive Cycle Rule: Prevent invalid cycles ($A \rightarrow B \rightarrow C$ where A, C same domain)

- Remove relationship with lower probability
- Classes within same domain should be disjoint

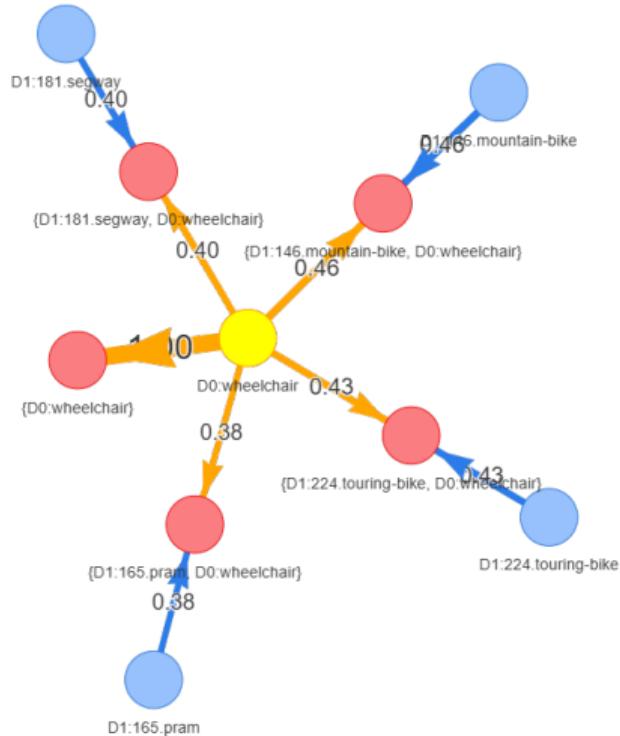
④ Unilateral Relationship Rule: Handle subset relationships ($A \rightarrow B$)

- Create universal class for shared concepts ($A \cup B$)
- Create universal class for unique concepts (B only)

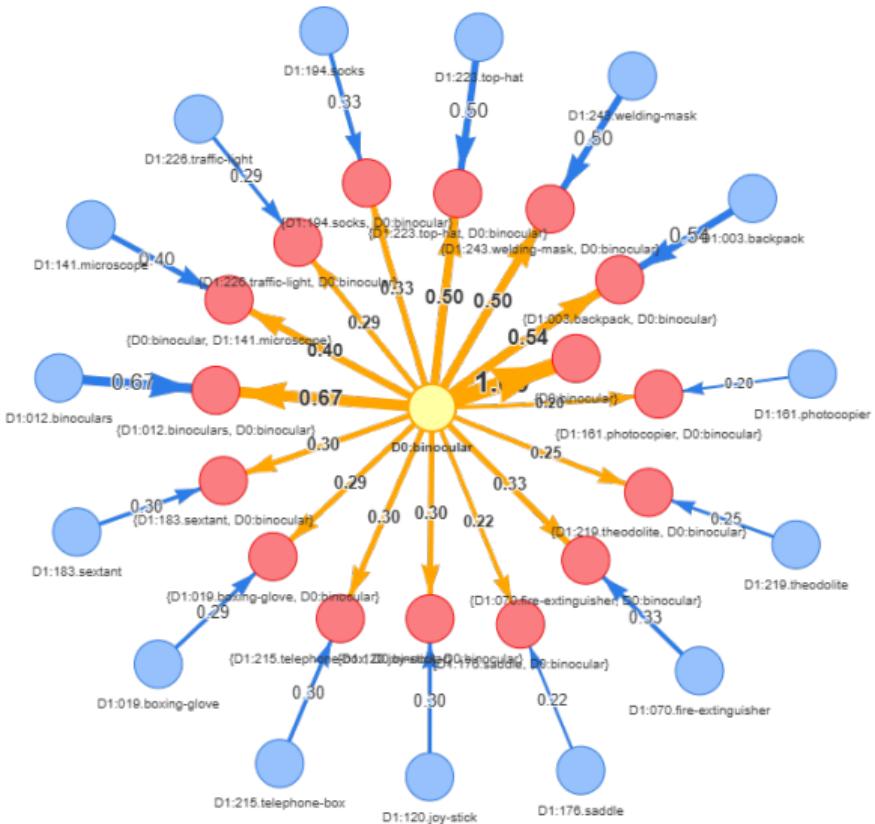
Taxonomy Visualization (Caltech-101 + Caltech-256)



Good Cluster



Bad Cluster



Universal Model Architecture

Baseline Model:

- 6-layer FC classifier
- Dropout regularization
- One-hot targets

Universal Model:

- 2-layer FC classifier
- No dropout
- Probability distribution targets

Target Generation: Convert domain labels to universal class distributions

$$\mathbf{t} = \hat{M}_i[j, :] \quad \text{where } \hat{M}_i(j, u) = \frac{M_i(j, u)}{\sum_{u'} M_i(j, u')} \quad (6)$$

Loss Function:

$$\mathcal{L} = - \sum_{u=1}^{|U|} \mathbf{t}(u) \log(\mathbf{p}(u)) \quad (7)$$

Multi-Domain Training Process

Training Procedure:

- ① Combine multiple datasets while preserving domain identity
- ② Each sample: $(\text{image}, (\text{domain_id}, \text{label})) \rightarrow (\text{image}, \text{universal_target})$
- ③ Train single model on unified dataset
- ④ Use domain-specific mapping matrices for target generation

Inference:

$$\mathbf{d}_i = M_i^T \mathbf{p} \quad (8)$$

$$\hat{c}_i = \text{argmax}(\mathbf{d}_i) \quad (9)$$

where \mathbf{p} are universal class predictions and \mathbf{d}_i are domain-specific predictions.

Universal Model Performance

Datasets: Caltech-101, Caltech-256, CIFAR-100

Cal-101 + Cal-256 Results

Taxonomy	Cal-101	Cal-256
Hypothesis	91.81 (+0.00)	82.84 (+13.36)
MCFP	91.23 (-0.58)	80.75 (+11.27)
MCFP Binary	92.73 (+0.92)	89.71 (+20.23)
Density	92.96 (+1.15)	81.54 (+12.06)
Naive	93.19 (+1.38)	82.25 (+12.77)

Cal-101 + Cal-256 + CIFAR Results

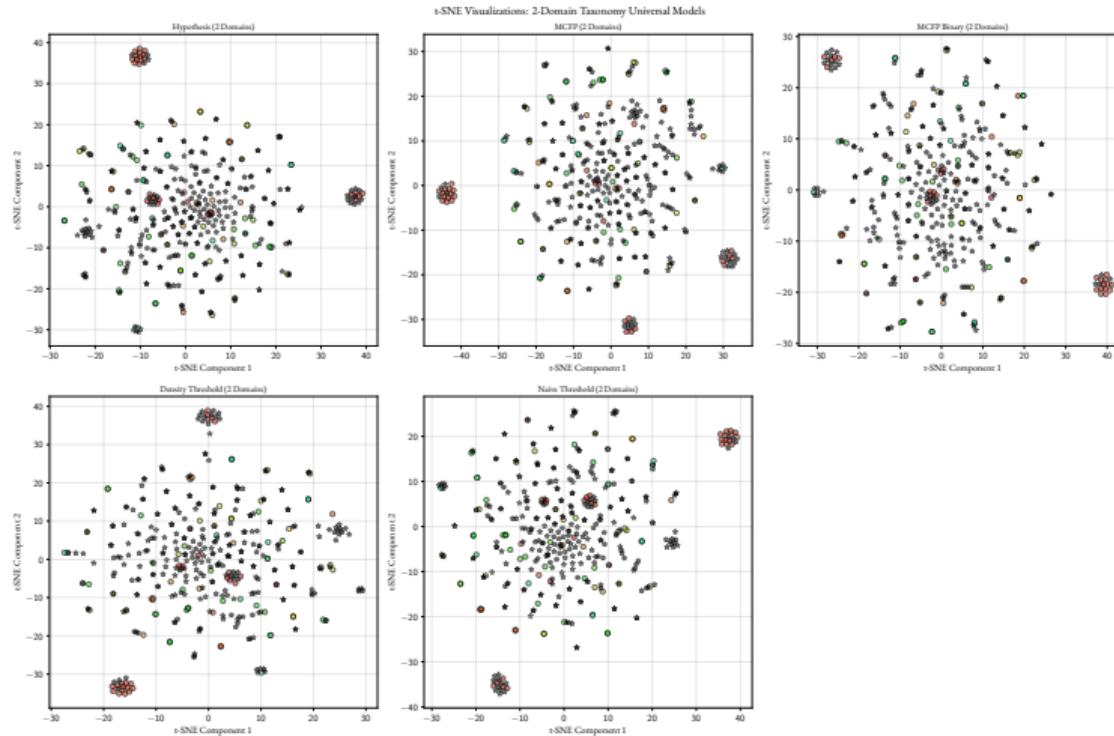
Taxonomy	Cal-101	Cal-256	CIFAR
Hypothesis	68.74 (-23.07)	58.17 (-11.31)	69.03 (+8.55)
MCFP	83.28 (-8.53)	76.50 (+7.02)	76.10 (+15.62)
MCFP Binary	94.58 (+2.77)	85.13 (+15.65)	82.71 (+22.23)
Density	95.39 (+3.58)	83.53 (+14.05)	83.14 (+22.66)
Naive	95.50 (+3.69)	85.36 (+15.88)	72.56 (+12.08)

Baselines: Cal-101: 91.81%, Cal-256: 69.48%, CIFAR-100: 60.48%

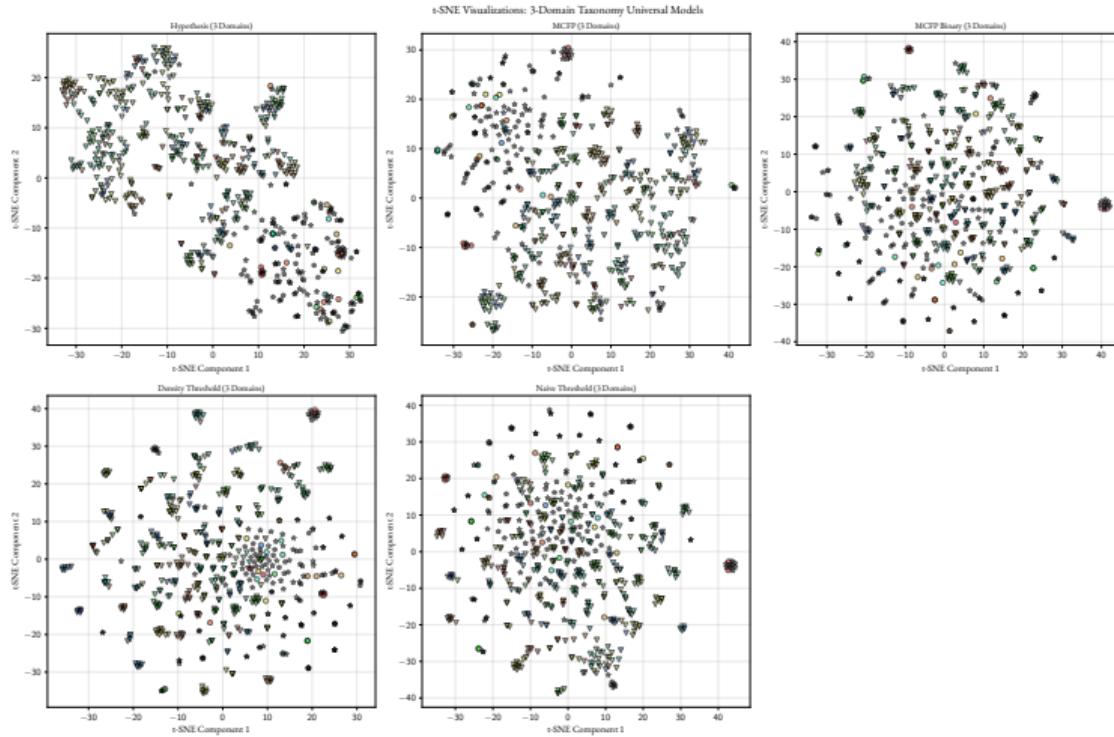
Key Findings:

- Universal models **outperform** single-domain baselines
- Different relationship selection methods excel on different datasets
- No single method consistently optimal across all scenarios

Feature Visualization with t-SNE (Caltech-101 + Caltech-256)



Feature Visualization with t-SNE (Caltech-101 + Caltech-256 + CIFAR-100)



Key Contributions

- ① **Novel Universal Model Approach:** Single model for multiple domains without task-specific heads
- ② **Comprehensive Relationship Selection Methods:** Four different approaches with systematic evaluation
- ③ **Synthetic Ground Truth Framework:** Controlled evaluation environment with domain-shifted variants
- ④ **Cross-Domain Prediction Pipeline:** Complete methodology from raw datasets to universal models
- ⑤ **Performance Validation:** Universal models outperform single-domain baselines

Main Findings

Successful Aspects:

- Universal models achieve better accuracy than single-domain models
- Cross-domain prediction effectively captures semantic relationships
- Synthetic datasets provide valuable controlled evaluation environment
- Feature visualizations show meaningful cross-domain clustering

Challenges Identified:

- No single relationship selection method works optimally for all cases
- Gap between evaluation metrics and actual model performance
- Parameter selection requires careful tuning for each dataset combination
- Some false positive relationships in generated taxonomies

Future Work & Improvements

Immediate Improvements:

- Grid search for optimal relationship selection parameters
- Develop better correlation between evaluation metrics and model performance
- Explore different universal model architectures

Extensions:

- Scale to larger datasets (ImageNet, COCO)
- Apply to other vision tasks (object detection, segmentation)
- Investigate dynamic relationship adjustment during training
- Explore unsupervised relationship discovery methods

Real-World Applications:

- Multi-domain medical imaging
- Cross-dataset autonomous driving
- Unified content moderation systems

Problem: Traditional image classification limited to single domains

Solution: Universal model trained on cross-domain taxonomy

Method: Cross-domain prediction → Relationship selection → Universal training

Results: Universal models outperform single-domain baselines

Thank you for your attention!

Questions?