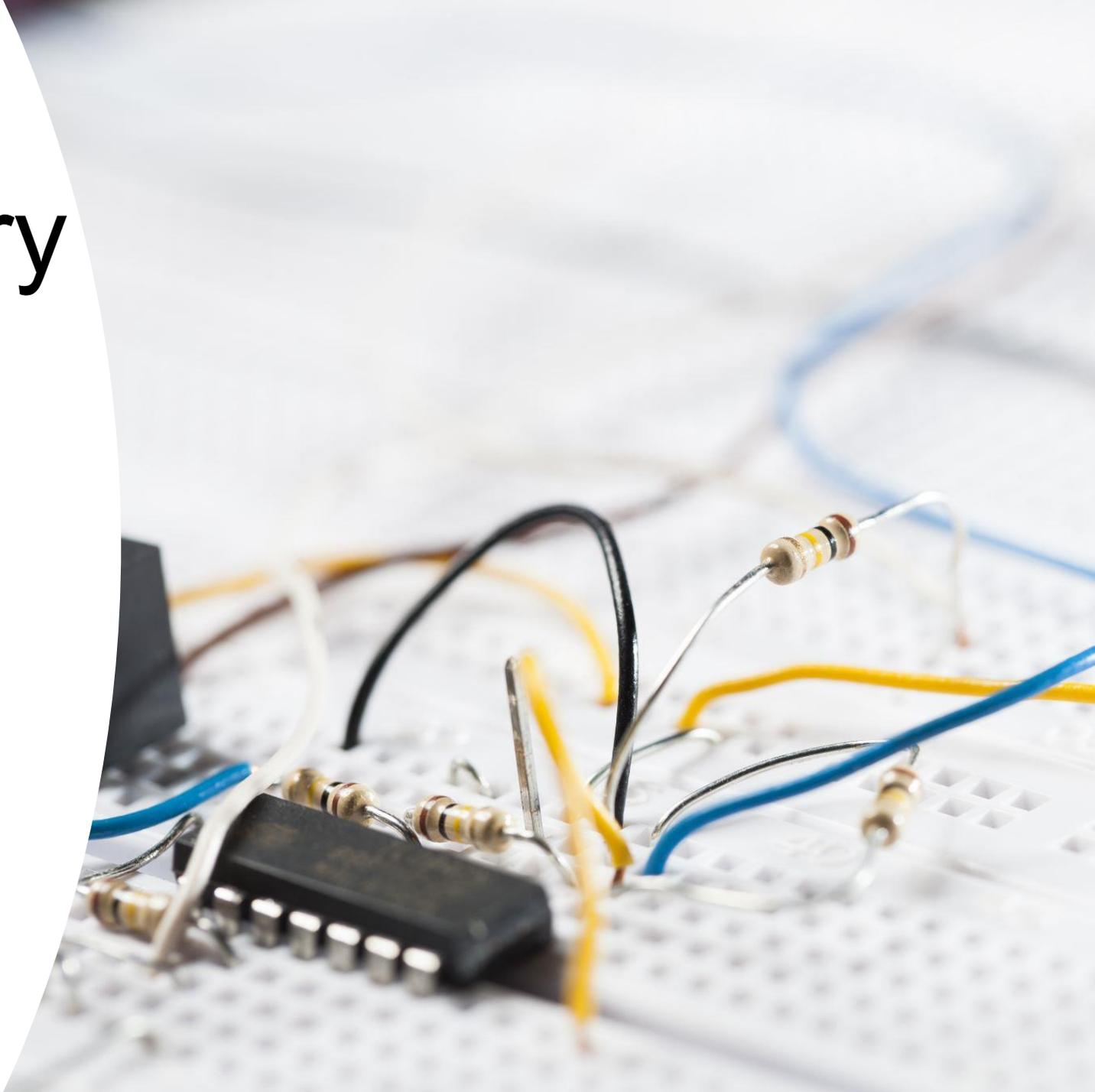


# TRM Compulsory Module

Research Methodology  
Research Question &  
Experimental Design

Dr. Mingshan Jia



# 1. Research Methodology

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# Agenda

- What is Research Methodology
- Methodology Vs. Method
- Types of Research Methodology
- Research Methodologies in ML

# What is Research Methodology?

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Research methodology is the overall strategy, theoretical framework, and justification that guide how a research study is designed and conducted.

- It answers both '**How?**' and '**Why?**'
- Key Components within a Research Methodology:
  - Overall Research Design
  - Data Strategy
  - Analytical Framework
  - Evaluation and Validation Strategy

Example: [Encoding edge type information in graphlets](#)

# Methodology Vs. Method

	Methodology	Method
<b>Definition</b>	The overall strategy, framework and justification for how we approach the research.	Specific techniques or procedures used for data collection, processing, analysis, and evaluation.
<b>Scope</b>	Broad and conceptual, guiding the entire research process.	Narrow and practical, focused on executing specific steps.
<b>Purpose</b>	Explains why certain approaches are chosen, and how they help address the research question.	Specifies what techniques and tools to use.
<b>Relationship</b>	Provides justification for the methods.	Implementation of the methodology.

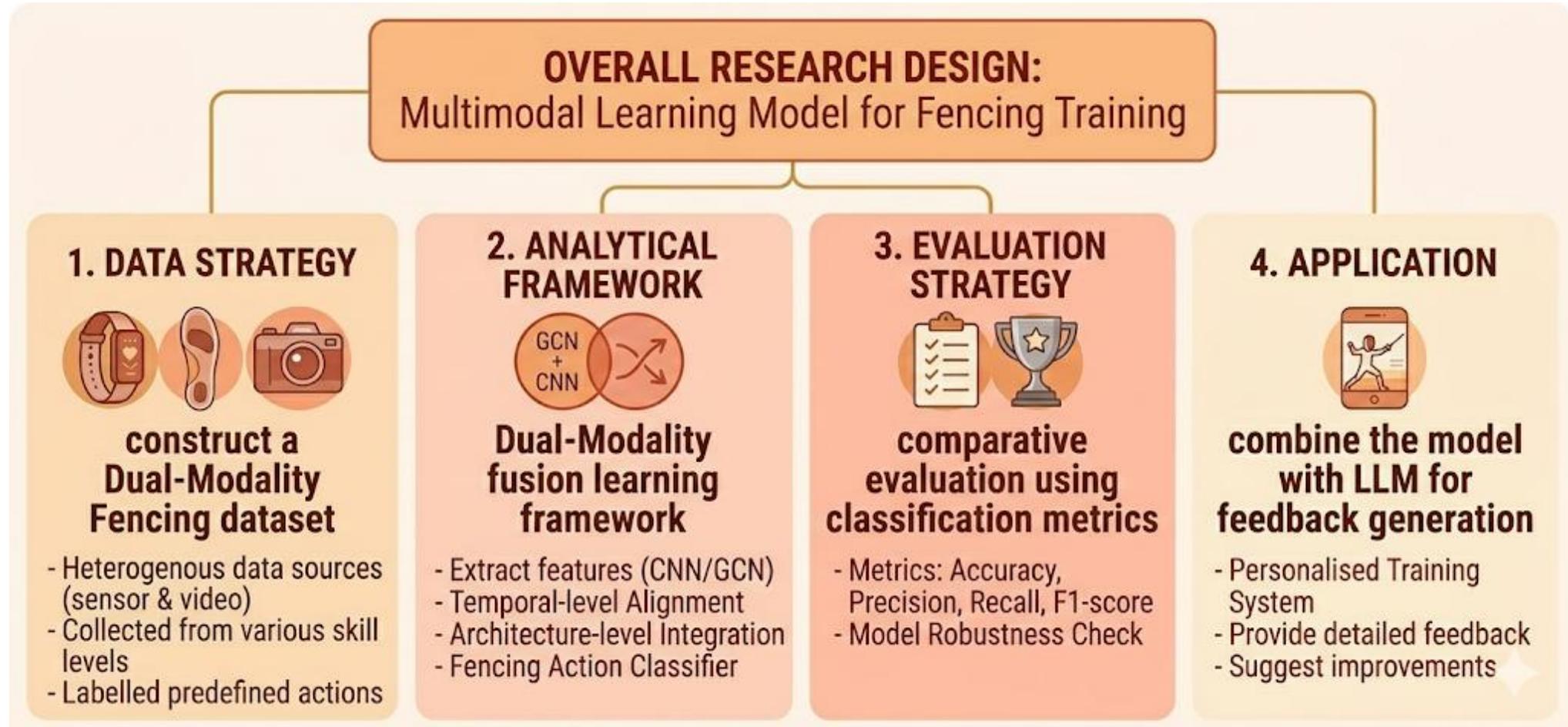
# Example: Multimodal Learning Framework for Fencing

Methodology (Strategy)	Method (Implementation)
Adopt a multimodal learning strategy to integrate heterogenous data sources.	Use smart bracelets, insoles to capture sensor data and use camera to record body posture and skeleton movement.
Construct a labelled multimodal dataset.	Collect data from fencers of various skill levels performing a predefined set of fencing actions.
Design a multimodal learning framework that integrates temporal and spatial feature.	Apply CNNs to extract features from sensor data, GCNs to process skeleton data, and a cross-attention mechanism to fuse temporal and spatial features.
Establish an evaluation protocol.	Use classification metrics such as accuracy, and F1-score.
Apply the model for personalised training feedback.	Integrate the model into a personalised training system, enhanced with LLM-generated feedback and improvement suggestions.

# Example: Multimodal Learning Framework for Fencing

Method (Implementation)	Methodology (Justification)
Use smart bracelets, insoles to capture sensor data and use camera to record body posture and skeleton movement.	Wearable sensors provide valuable kinematic information, while cameras capture detailed skeletal motion; combining them enables complementary multimodal representation.
Collect data from fencers of various skill levels performing a predefined set of fencing actions.	A diverse dataset ensures the model generalises well to different fencers and movements.
Apply CNNs to extract features from sensor data, GCNs to process skeleton data, and a cross-attention mechanism to fuse temporal and spatial features.	CNNs are effective for local feature extraction in temporal signals, while GCNs capture structural relationships in skeleton data, and cross-attention facilitates effective multimodal fusion.
Use classification metrics such as accuracy, and F1-score	Accuracy measures overall correctness, while F1-score balances precision and recall, which is crucial for imbalanced datasets.
Integrate the model into a personalised training system, enhanced with LLM-generated feedback and improvement suggestions.	LLMs can be fine-tuned as a fencing expert and thus can offer personalised training guidance based on the recognised action and skill level.

# Research Methodology: Diagram



# Types of Research Methodology

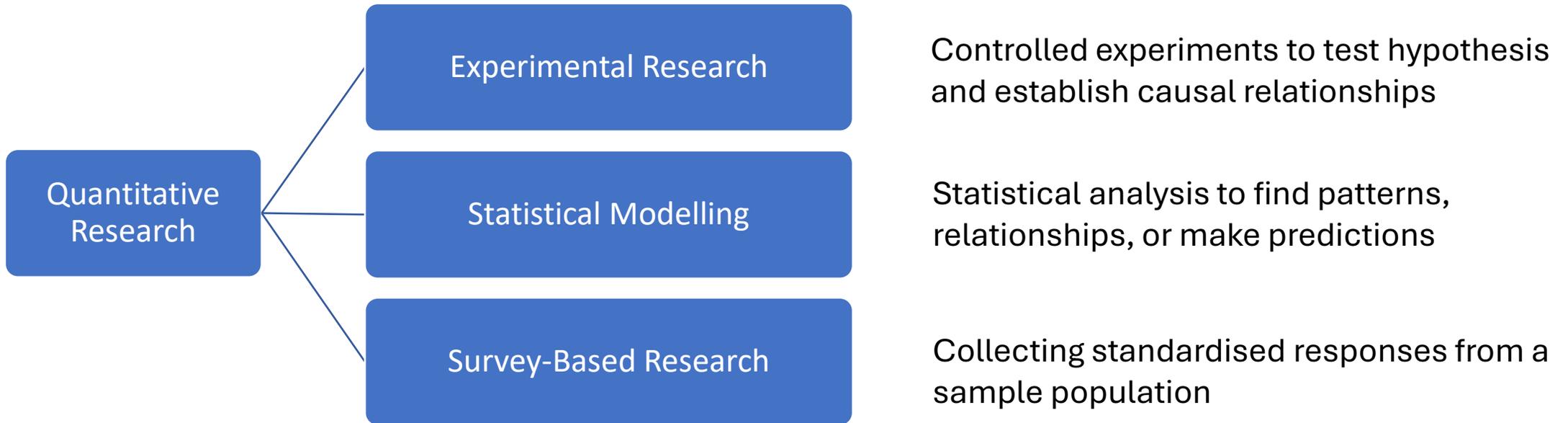


# Qualitative Methodology

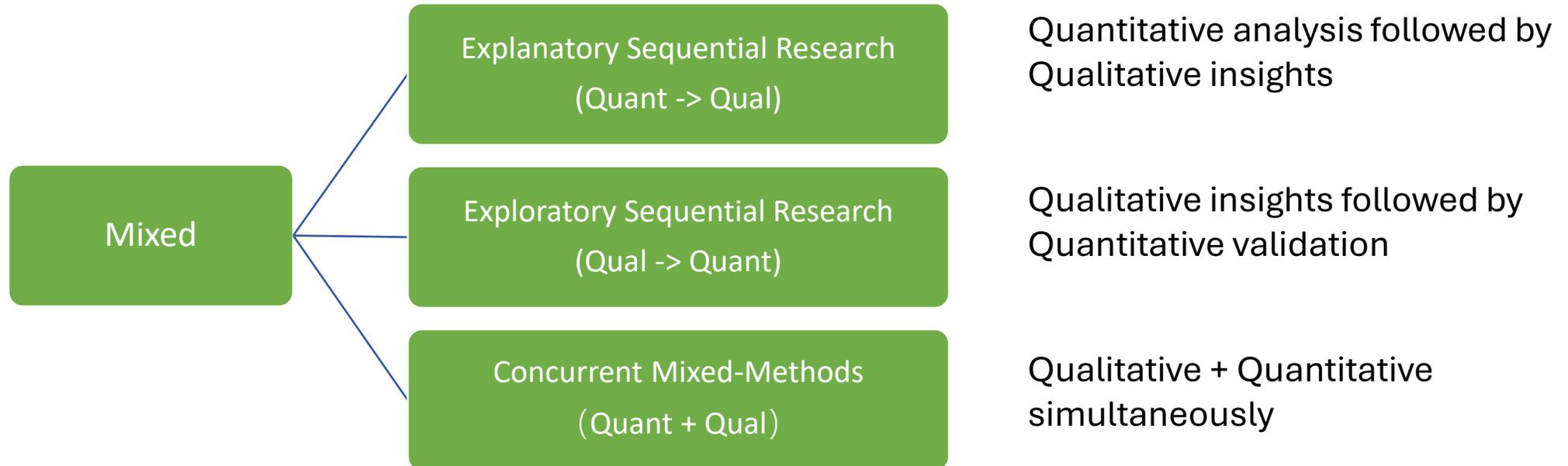
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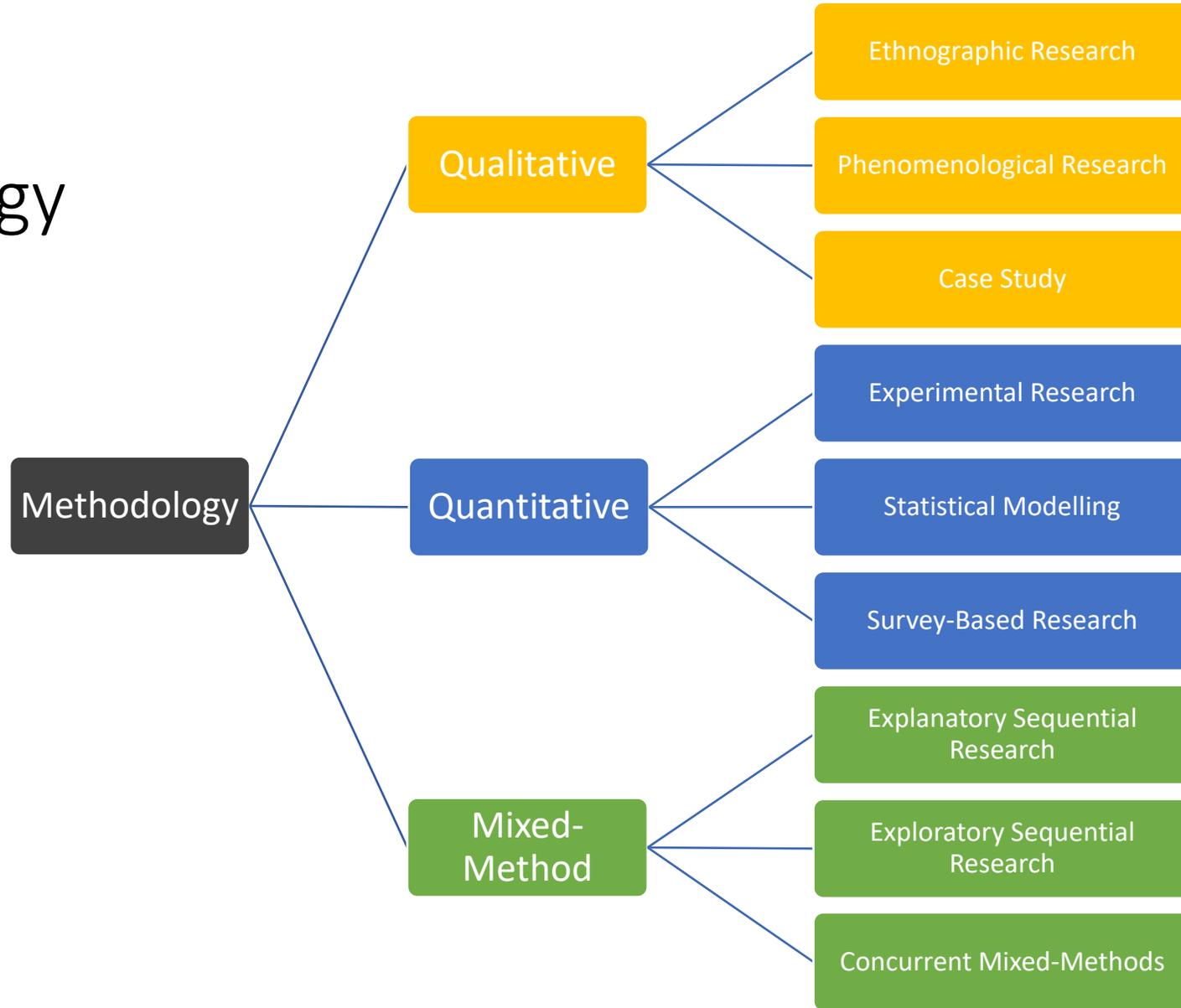
# Quantitative Methodology



# Mixed-Method Research Methodology



# Types of Research Methodology



# Research Methodology in ML Projects

Experimental Research

Survey-Based Research

Ethnographic Research

Statistical Modelling

Case Study

Phenomenological Research

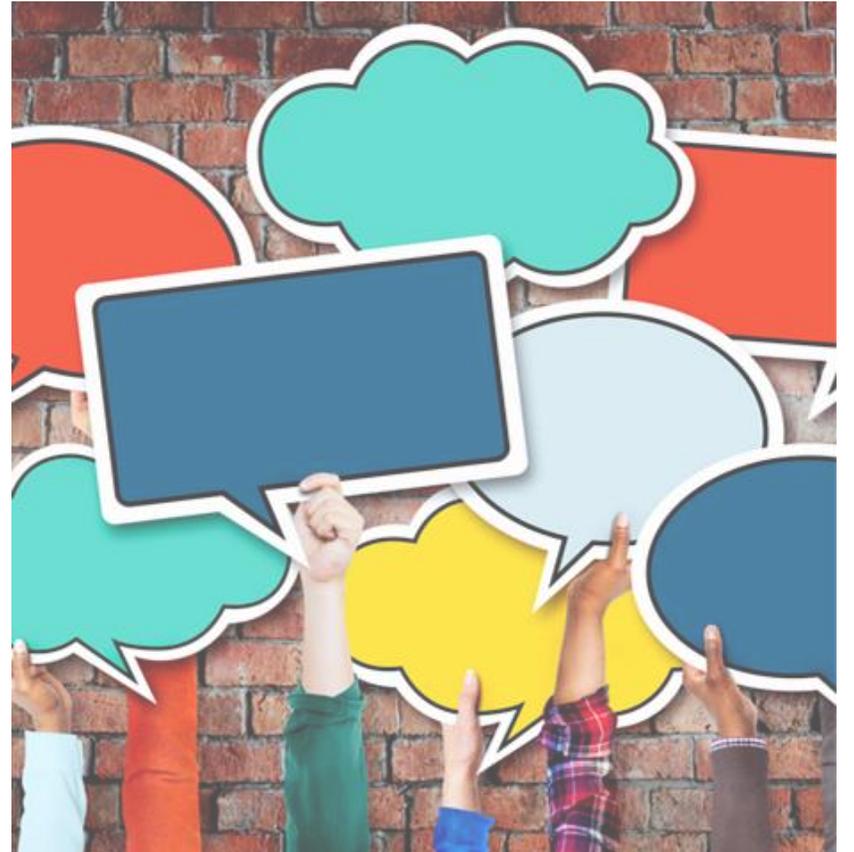
Mixed-Methods

# Activity

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Design a Research Methodology:

- Focus specifically on the four key components:
  1. Overall Research Design
  2. Data Strategy
  3. Analytical Framework
  4. Evaluation and Validation Strategy



## 2. Research Question

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# Agenda

- What is a Research Question?
- Research Question, Aim, and Objectives
- Characteristics of a Good RQ
- From Broad Topic to Research Question
- Research Questions in ML/AI

# What is a Research Question?

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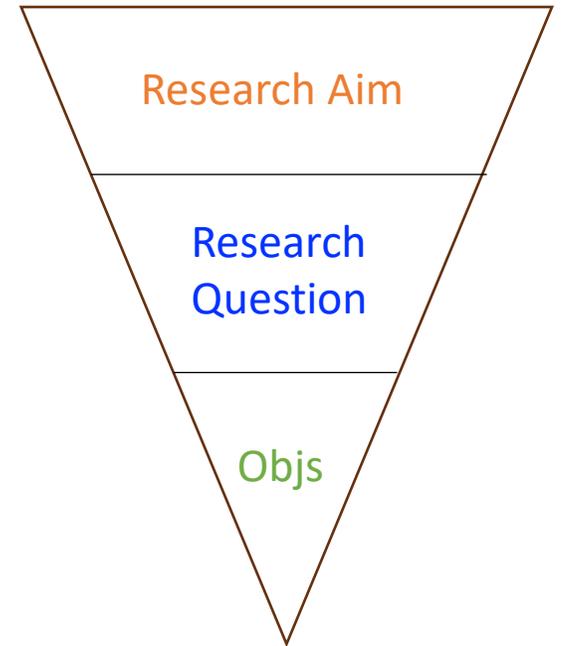
A specific and focused question that the research seeks to answer.

- It's a focal point that we can concentrate our efforts towards.
- It is specific so that it can guide our methodological choices.
- A research question should address an identified research gap.

# Research Question, Research Aim, and Research Objectives

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- **Research Aim:** A broad statement of what the research intends to achieve.
- **Research Question:** A specific and focused question that the research seeks to answer.
- **Research Objectives:** A set of actionable and measurable tasks to help answer the Research Question.



# Example: Measuring Quadrangle Formation in Complex Networks

<https://arxiv.org/pdf/2011.10763>

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## Research Aim:

- The study aims to develop and analyse new metrics for quantifying quadrangle formation in complex networks.

## Research Question:

- How to propose a novel quadrangle formation metric that aligns with clustering coef. and closure coef. in triangle formation?
- How the proposed metric can be used in network analysis and learning tasks?

## Research Objectives:

- Develop new metrics for quadrangle formation, according to the position of focal node.
- Compare the proposed metric with classic triangle formation metrics across different types of real networks, and analyse its characteristics.
- Evaluate the effectiveness of proposed metrics in network classification and link prediction tasks.



# Characteristics of a Good Research Question



## **Focused and Specific:**

Clearly states what you want to find out.



## **Relevant and Not Answered:**

Tied to a gap in the literature or a pressing problem.



## **Researchable and Feasible:**

Can be investigated based on existing methods, data, and analysis tools.

# Example 1

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## FineTuning Text-to-Image Diffusion Models for Fairness (ICLR 2024)

Research Question: *How can we fine-tune text-to-image diffusion models to mitigate bias in a controllable manner, aligning specific attributes of the generated images (e.g., gender, race, age) with a user-defined target distribution?*

# Example 2

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**The devil is in the neurons: interpreting and Mitigating social biases in pre-trained language Models (ICLR 2024)**

Research Question:

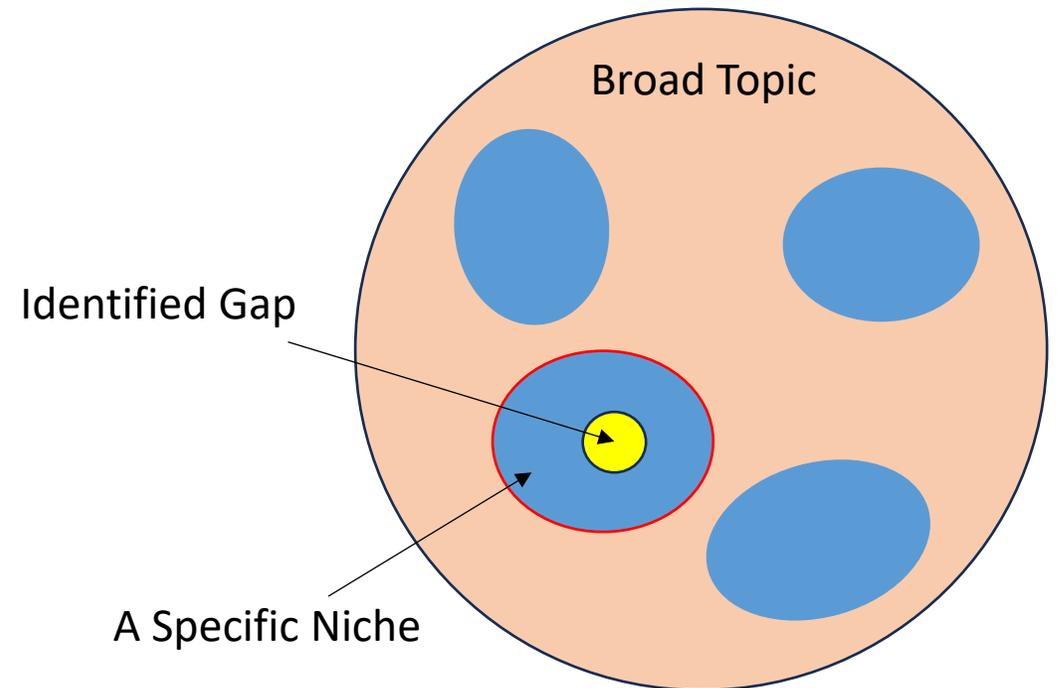
*(1) How to precisely identify the social bias neurons in PLMs?*

*(2) How to effectively mitigate social biases in PLMs based on the identified bias neurons?*

# From Broad Topic to Research Question

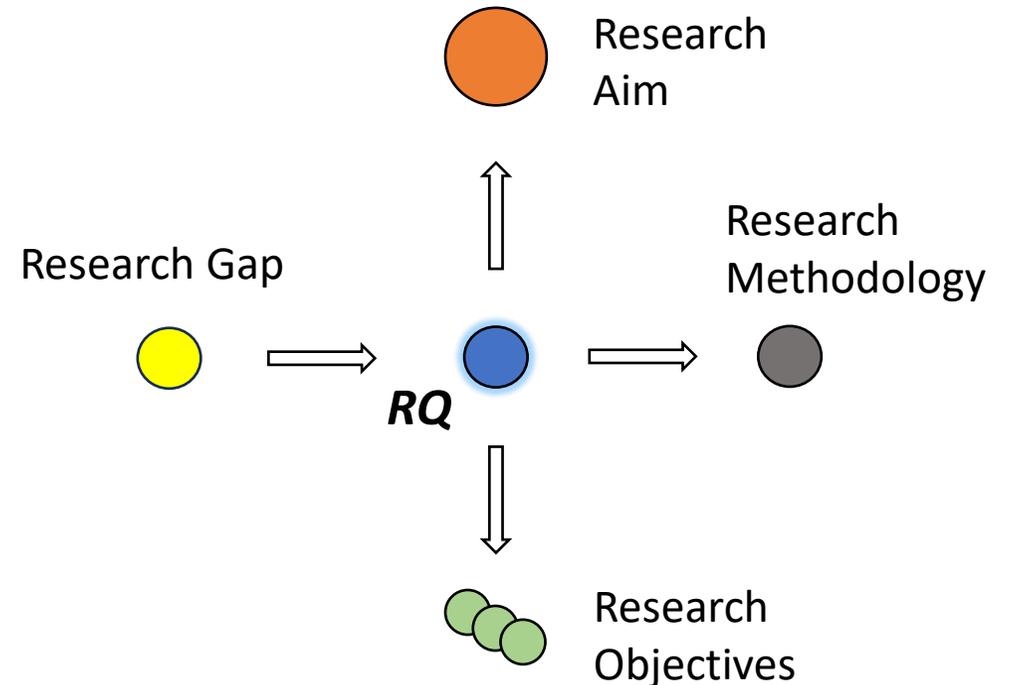
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1. Start with a topic of interest
  2. Learn more about the topic and narrow down to a specific niche
  3. Dig deep and Identify a gap
- ↓
4. Craft a research question to bridge the identified gap



# Research Question's Core Position

- A **Research Question** originates from a Gap.
- Research Aim is generalised from the **RQ**.
- Research Objectives are derived by breaking down the **RQ**.
- Research Methodology is chosen based on the nature of the **RQ**.



# Active Research Questions in ML/AI

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- How can we scale neural networks to have a vast number of parameters without increasing computational overhead? ([Mixture-of-Experts](#))

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- How can we continuously adapt pretrained models to new data without losing previously learned knowledge? ([Continual Pretraining](#))

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- How can human preferences be integrated into learning models to align their outputs with user needs? ([RLHF](#))

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- How can test-time computation be used to improve model outputs? ([Inference-Time Computation, RAG](#))

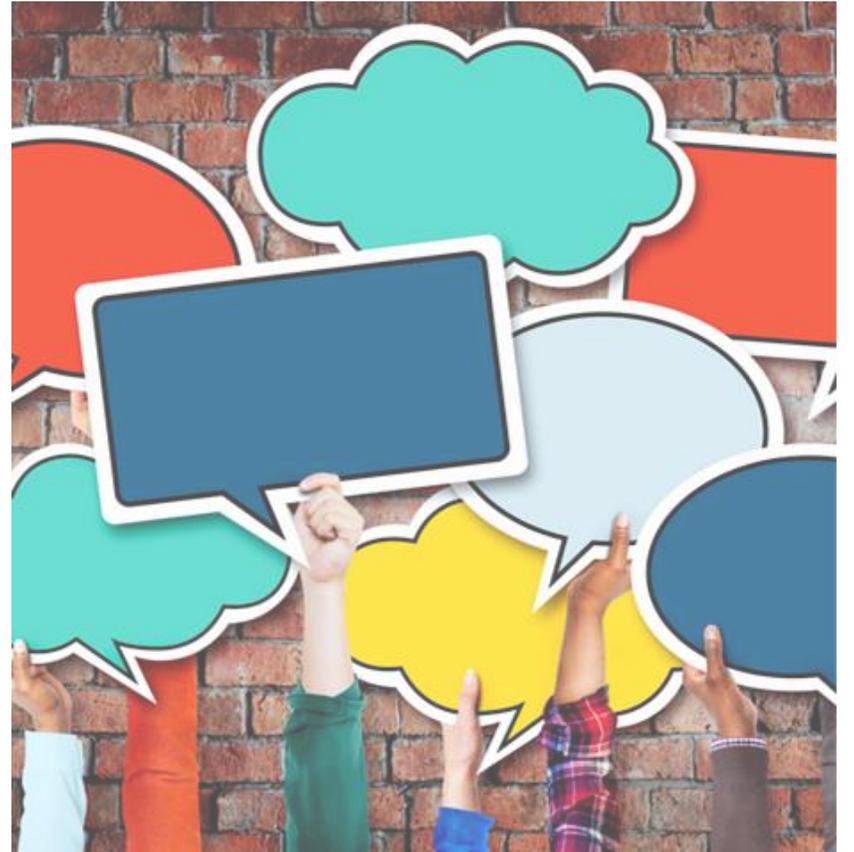
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- How can we transfer the performance of large, complex models into smaller, computationally efficient models? ([Knowledge Distillation](#))

# Activity

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## Formulate a Research Question:

- When designing your research question, consider the key characteristics:
  1. Is the question focused and specific?
  2. Does it address a relevant research gap?
  3. Is it researchable and feasible with available data and methods?
- Then, break the research question down into several research objectives.



# 3. Experimental Design

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# Agenda

- What is Experimental Design?
- Basic Concepts of Experiment Design
- What is a Good Research Design?
- An Example
- Experiment Design in ML/AI

# What is Experimental Design?

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The systematic planning of an experiment to ensure that the results obtained are valid, reliable, and capable of answering the research question.

- It is the blueprint for implementing and conducting experiment.
- An experiment is designed to establish **cause-and-effect** relationships.
- Experimental results should be able to **answer the research question**.

# Experiment Design Basics

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## Independent variable and dependent variable

- IV: The factor manipulated by the researcher (cause)
- DV: The outcome measured (effect)

## Control group and experiment group

- Control group: No special treatment, used for comparison
- Experiment group: Receiving the treatment or change

## Blinding in Experiments

- Double-Blind: Neither participants nor experimenters know who receives treatment.
- Triple-Blind: Participants, experimenters, and analysts don't know.

# What is a Good Experimental Design?

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## Clearly Defined and Well-Structured

- Clearly outlines variables, groups, and procedures.
- Leaves no ambiguity in execution.

## Producing Measurable Outcomes

- Uses quantifiable metrics for evaluation.
- Outcomes should be able to answer the research question.

## Methodologically Sound and Unbiased

- Proper choice of data and all procedures.
- Fair comparison between groups.

## Replicable and Reproducible

- All steps are transparent and well-documented

# Design Experiments to Answer the RQ: Example

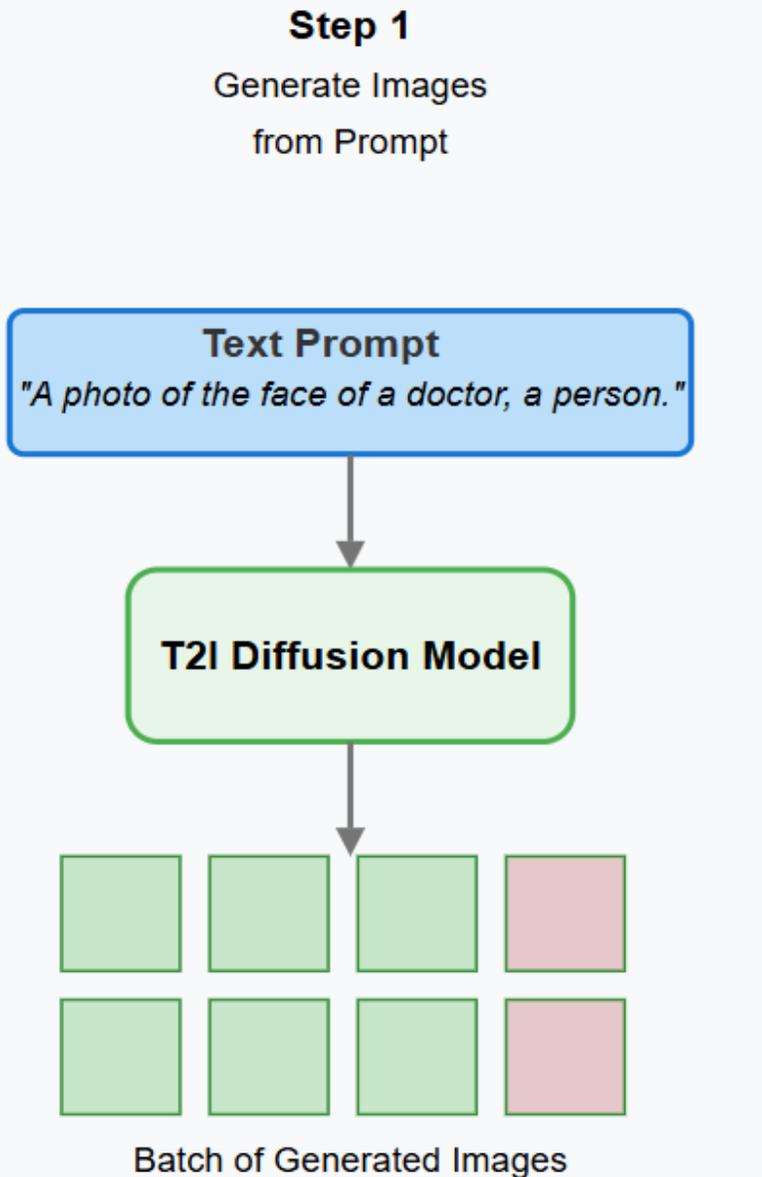
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## FineTuning Text-to-Image Diffusion Models for Fairness (ICLR 2024)

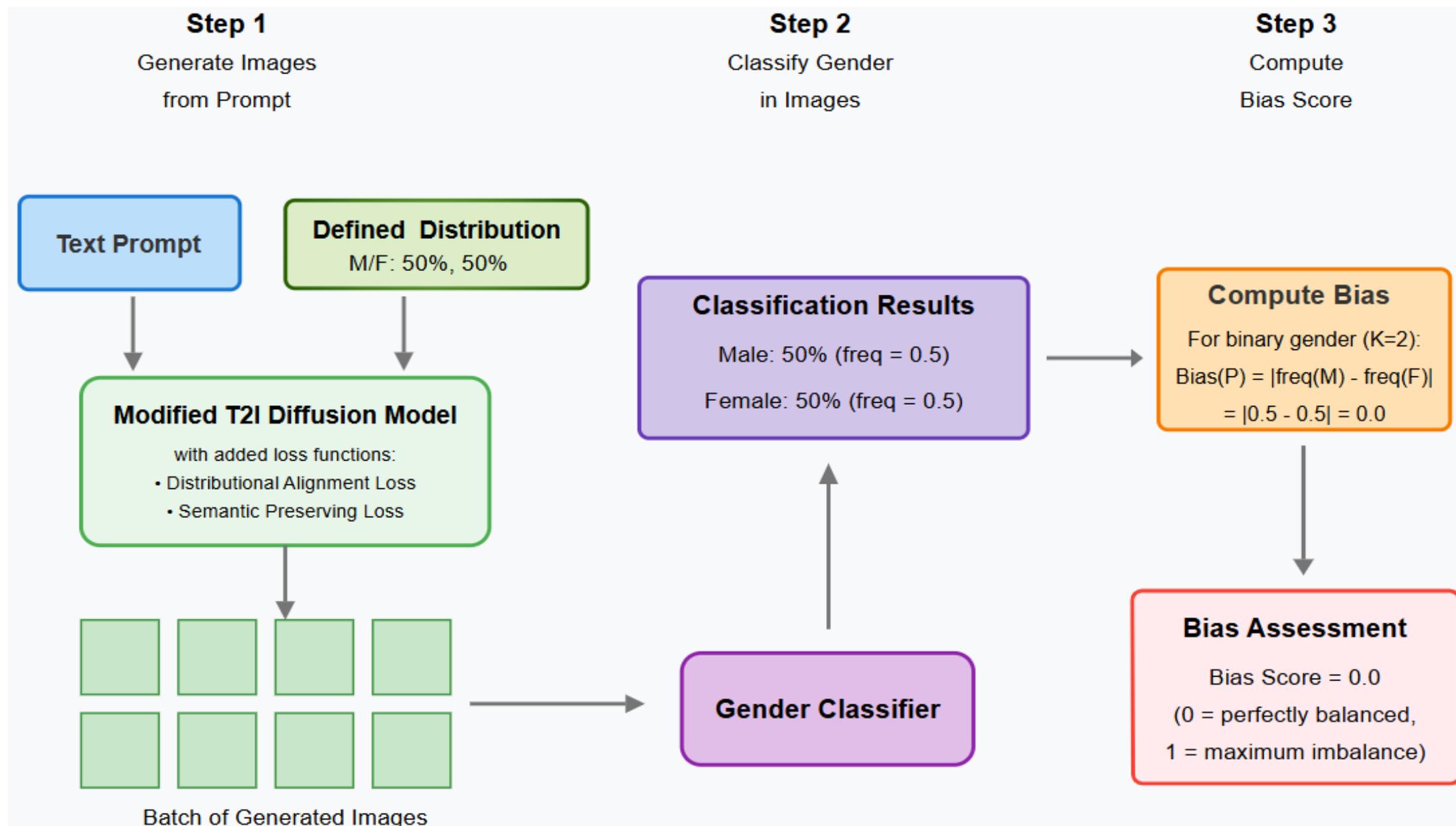
**Hypothesis:** *Biases in T2I diffusion models can be mitigated in a controllable manner through finetuning.*

**Research Question:** *How can we fine-tune text-to-image diffusion models to mitigate bias in a controllable manner, ensuring that generated images align with a user-defined target distribution for attributes such as gender, race, and age ?*

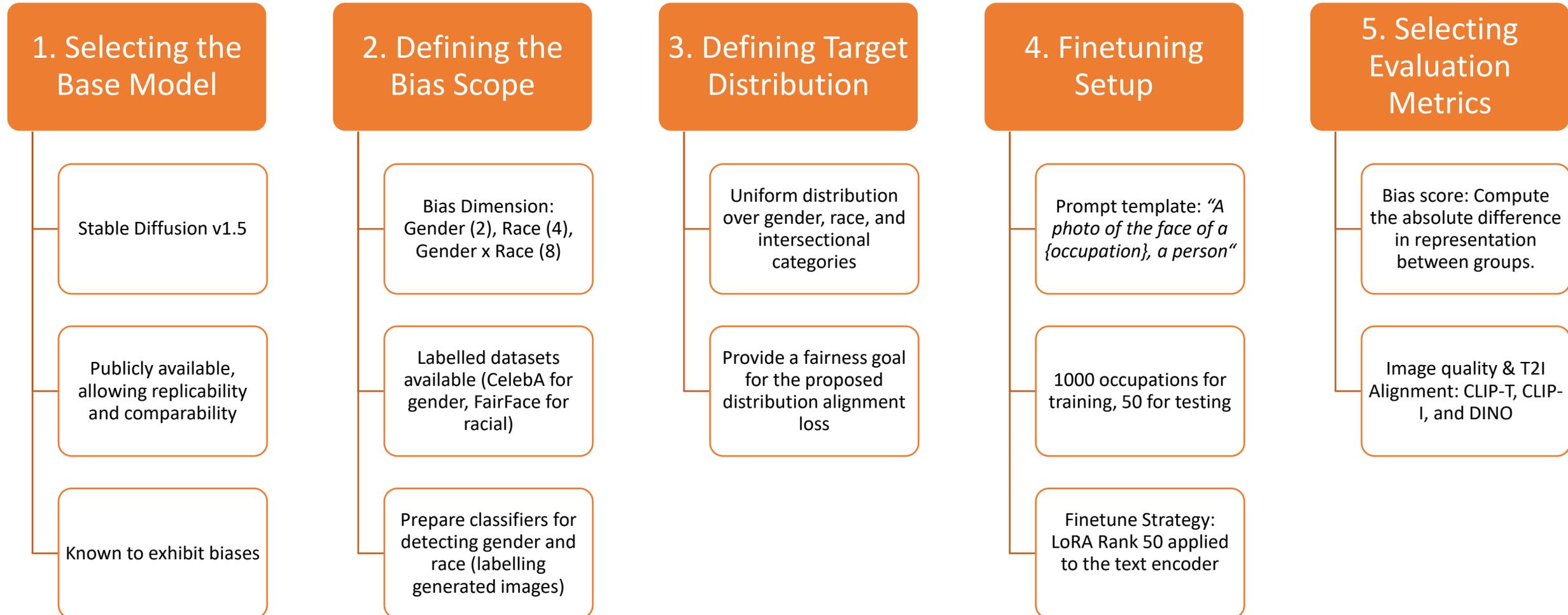
# Understanding the Task: T2I Bias Assessment Process



# Experiment Pipeline



# Design Choices: Exp 1 Mitigating gender and race bias in occupation



# FineTuning T2I Diffusion Models for Fairness

Prompt with unseen occupation: “a photo of the face of an electrical and electronics repairer, a person”.

Original



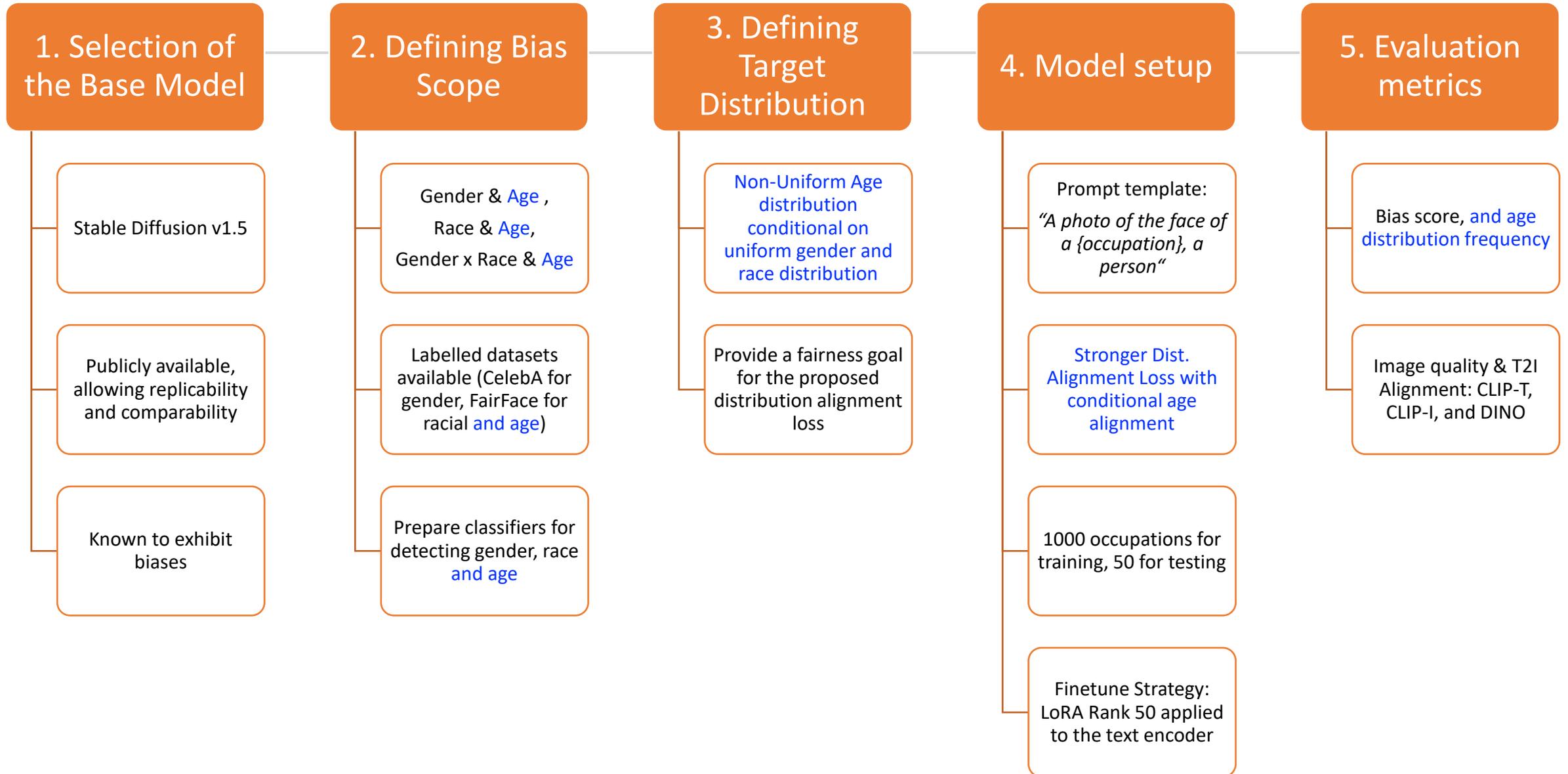
Gender bias: 0.84  
Racial bias: 0.48  
Gender×Race bias: 0.24

Debiased



Gender bias: 0.11  
Racial bias: 0.10  
Gender×Race bias: 0.06

# Design Choices: Exp 2 Non-Uniform Distributional Alignment of Age



# Design Choices: Exp 2 Non-uniform Distributional Alignment Of Age

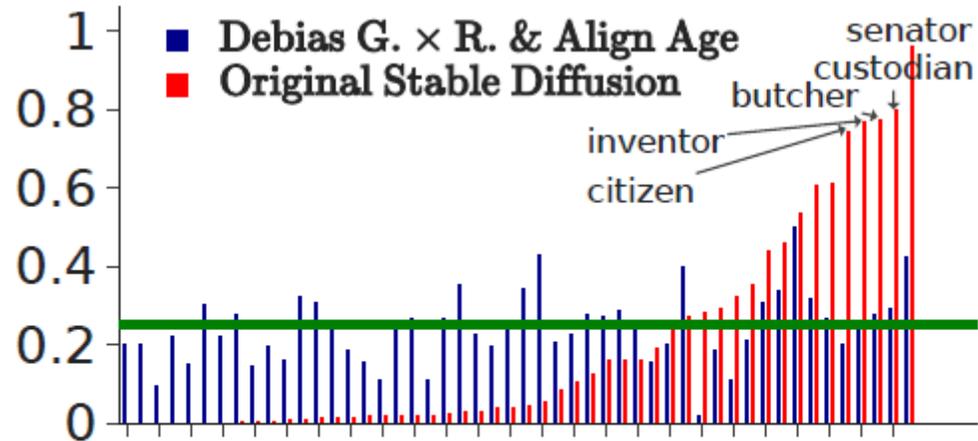


Figure 4: Freq. of Age=old from generated images. X-axis denotes occupations. Green horizontal line (25%) is the target.

Table 5: Aligning age distribution to 75% young and 25% old besides debiasing gender & race.

Method	Bias ↓			Freq.	Semantics Preservation ↑		
	Gender	Race	G.×R.	Age=old	CLIP-T	CLIP-I	DINO
Original SD	.67±.29	.42±.06	.21±.03	.202±.263	.39±.05	—	—
Debias G.×R.	.16±.13	.09±.04	.06±.02	.147±.216	.39±.05	.67±.15	.58±.22
→ Debias G.×R. & Align Age.	.15±.12	.09±.04	.06±.02	<u>.248±.091</u>	.38±.05	.66±.16	.58±.23

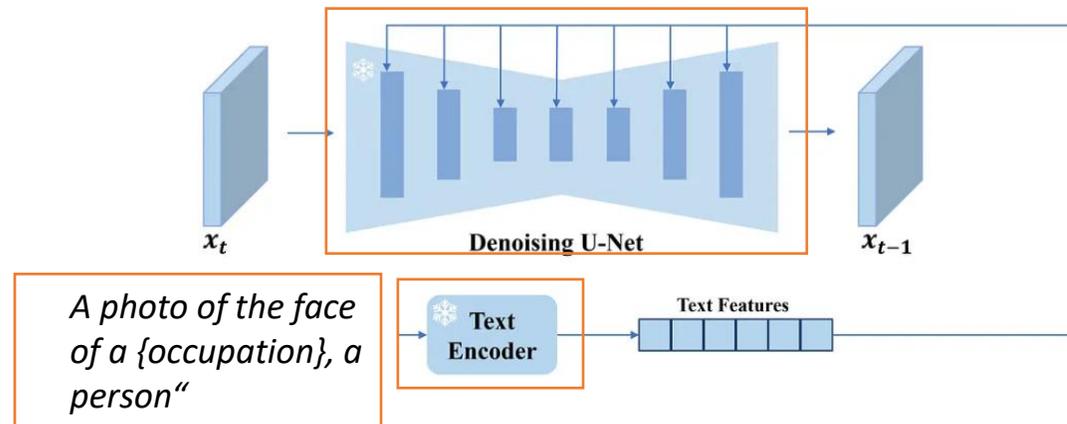
# Design Choices: Additional Experiments

## Exp 3: Generalisation for multiple faces

- Simply change the test prompt template to “A photo of the faces of two/three {occupation}, two/three people”

## Exp 4: Ablation on Different Components to Finetune

- Prompt Prefix, Text Encoder, U-Net, Text Encoder & U-Net



## Exp 5: Generalisation for multiple concept

- Simply including different types of prompts in the finetuning data

# Design Choices: Extra Experiments

## Exp 3: Generalisation to multiple faces

Table 3: Eval on multi-face image generation.

Pro- mpt	Model	Bias (single face) ↓			Bias (all faces) ↓			S. P. ↑
		Gender	Race	G.×R.	Gender	Race	G.×R.	CLIP-T
Two ppl	SD	.46±.28	.45±.04	.21±.02	.43±.26	.45±.03	.21±.02	.40±.04
	Ours	.26±.16	.14±.06	.09±.03	.18±.14	.15±.06	.08±.03	.41±.04
Three ppl	SD	.48±.32	.44±.05	.21±.02	.42±.28	.44±.04	.21±.02	.40±.05
	Ours	.26±.17	.16±.05	.09±.02	.16±.14	.19±.06	.10±.02	.41±.05

## Exp 5: Generalisation to multiple concepts

Table 6: Debiasing gender, racial, and intersectional biases for multiple concepts at once.

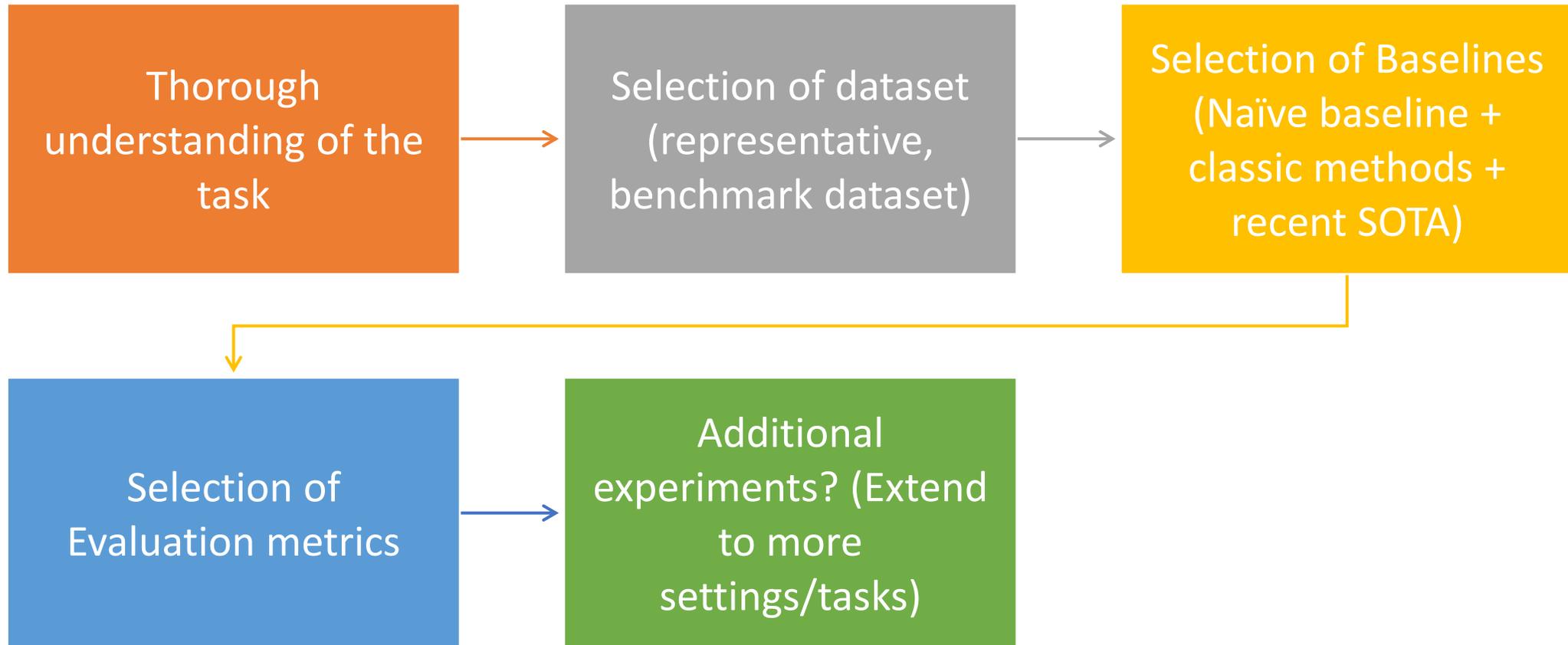
	Occupations				Sports				Occ. w/ style & context				Personal descriptors			
	Bias ↓		S. P. ↑		Bias ↓		S. P. ↑		Bias ↓		S. P. ↑		Bias ↓		S. P. ↑	
	G.	R.	G.×R.	CLIP-T	G.	R.	G.×R.	CLIP-T	G.	R.	G.×R.	CLIP-T	G.	R.	G.×R.	CLIP-T
SD	.67 ±.29	.42 ±.06	.21 ±.03	.38 ±.05	.56 ±.28	.38 ±.05	.19 ±.03	.35 ±.06	.41 ±.26	.37 ±.08	.18 ±.03	.43 ±.05	.37 ±.26	.36 ±.06	.17 ±.03	.41 ±.04
Ours	.23 ±.18	.10 ±.04	.07 ±.02	.38 ±.05	.37 ±.23	.11 ±.06	.08 ±.04	.35 ±.05	.31 ±.20	.19 ±.07	.11 ±.03	.42 ±.05	.18 ±.17	.13 ±.06	.07 ±.03	.41 ±.04

## Exp 4: Ablation on Different Components to Finetune

Table 4: Finetuning different SD components. For prompt prefix, five soft tokens are finetuned. For others, LoRA w/ rank 50 is finetuned.

Finetued Component	Bias ↓	Semantics Preservation ↑		
	Gender	CLIP-T	CLIP-I	DINO
Original SD	.67±.29	.39±.05	—	—
Prompt Prefix	.24±.19	.39±.05	.70±.15	.62±.22
Text Encoder	.23±.16	.39±.05	.77±.15	.70±.22
U-Net	.22±.14	.39±.05	.90±.09	.87±.13
T.E. & U-Net	.17±.13	.40±.04	.80±.14	.74±.20

# Experimental Design in ML/AI

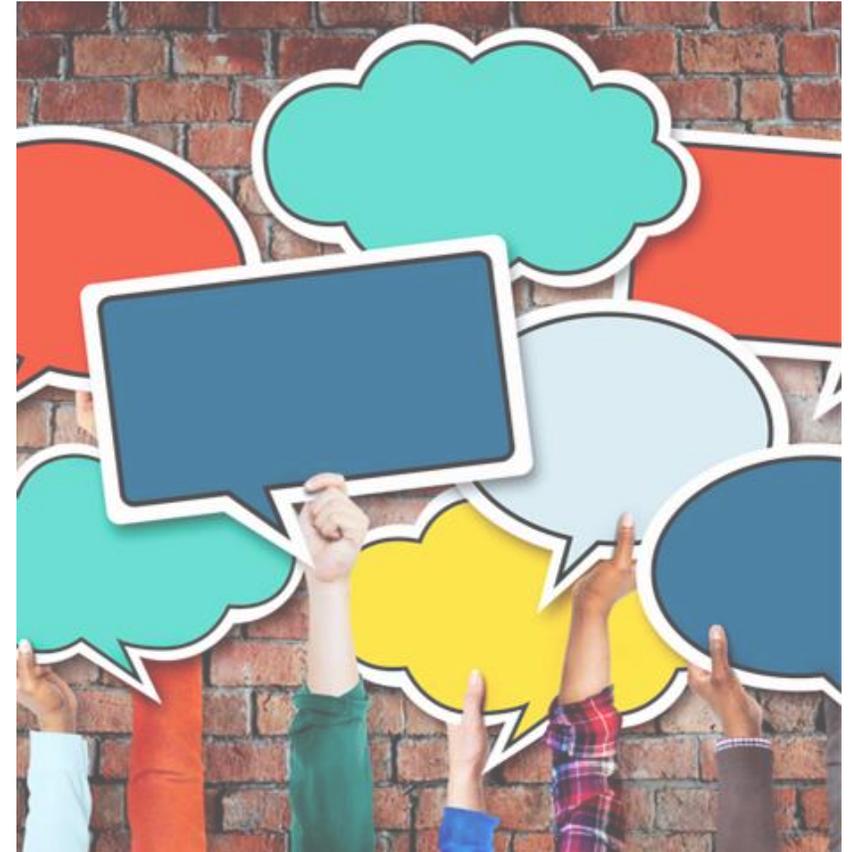


# Activity

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Choose a research paper that interests you, and analyse how the experiments serve to answer the research question(s).

- What is the experimental task, and what is the control setup?
- What are the key design choices, and why were these choices made?
- Upload documents if needed.





Questions?