

# EXPLORING MULTI-MODAL NEURAL MODELS AND THEIR APPLICATIONS



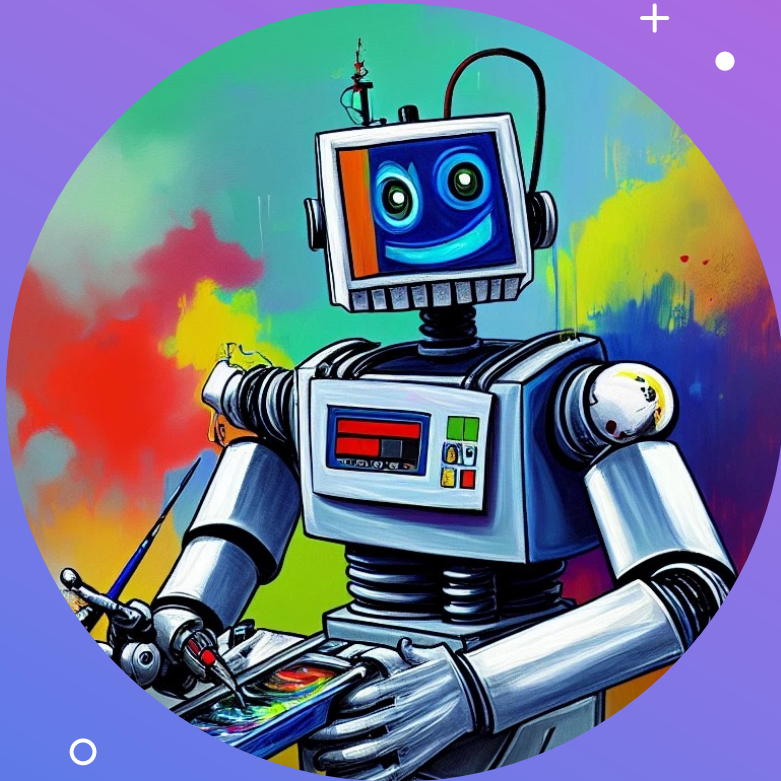
Lectures on Computational Linguistics

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LUCIA C. PASSARO  
ALESSANDRO BONDIELLI

`{lucia.passaro,alessandro.bondielli}@unipi.it`



# OUTLINE

## MULTIMODALITY AND NLP(LAB 2)

### Part I

Motivation and background

Problems and tasks

Data and pipelines



# OUTLINE

MULTIMODALITY AND NLP(LAB 2)

## Part II

Learning strategies for VL models

Specializing pre-trained models

Generative models



# Motivation and background

# Motivation: humans and modalities

- Humans perceive the world through **many channels**, such as visual, haptic, and auditive
- Individual channels are typically **incomplete** and **noisy**
- Humans align and fuse information collected from multiple channels and grasp the **key concepts for interpreting the world**



# Multi-modality

- Multi-modality involves the co-occurrence and co-operative use of different semiotic and perceptual modes.
- It is a rising concept in current NLP research, since it is relevant from two perspectives:
  - The Cognitive perspective: **mental concepts are multi-modal constructions** (grounded cognition; Barsalou, 2008).
  - The Communication perspective: **communication is inherently multi-modal**, especially on the Web (multi-modal discourse analysis; Benson, 2016).

*“One of the core aspirations in AI is to develop algorithms that endow computers with an ability to effectively learn from multi-modal (or, multi-channel) data.”*

Gan et al., 2022

# Background: intuitions and keywords

- Word / Visual Semantic embeddings
- Semantics and Similarity



# Embeddings

“In the neural network literature, **any information “embedded” in a low-dimensional vector space.**

Broadly speaking, all implicit distributional vectors are embeddings; in a narrow sense, word embeddings are distributional vectors built with neural networks”

Lenci, 2018

# (word) embedding

- **Word embeddings** are the most common text encoding technique when working with artificial neural networks.
- They are **dense representations** of words (vectors), and are learnt by employing textual information.
- **Similar** words (i.e., having a similar **meaning**) have similar embeddings
  - Similarity is measured with **cosine**

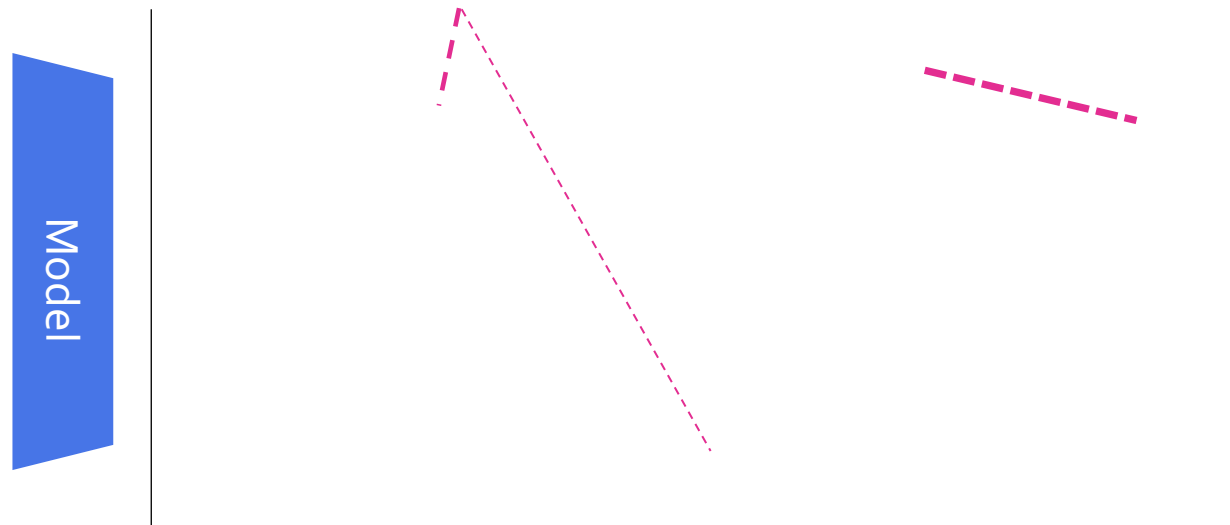
# (image) embedding

- An image embedding is a low-dimensional representation of an image
- Similar to a word embedding, it is a dense vector representation of the image which can be used for many tasks
- Similar images have similar embeddings
  - Similarity is measured with cosine

# (word) embeddings

- Once the model is built, we can use embeddings to represent linguistic events (tokens, phrases, texts...) within the same distributional space
- This allows for measuring the distance (and the similarity) among the events

I love Artificial Intelligence  
Mathematics is complex  
I like AI  
I study math  
I'm confused, now



# (image) embeddings

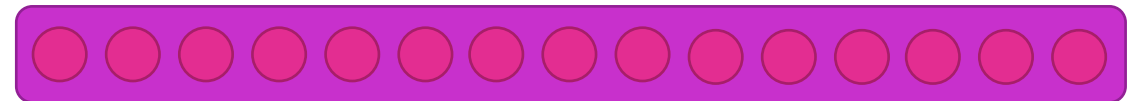
- Intuitively, the same idea has been applied over the years to images
  - Using a model trained on (lots of) visual data
  - We construct a «mathematical» representation of images based on probabilities



# (visual-semantic) embeddings

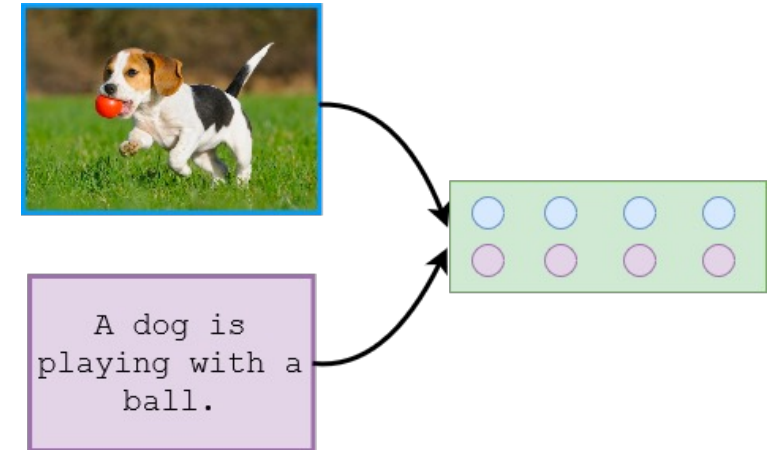
How can word embeddings (and textual representations in general) be enriched with **extra-linguistic (e.g., visual) information?**

...  
a young tennis player preparing to  
serve a tennis **ball** to her opponent  
a tennis player leaps up to return the  
**ball**  
a tennis player is trying to hit a **ball**  
with a tennis racket  
...



# (visual-semantic) embeddings

- Visual-semantic embeddings (aka multi-modal embeddings) encode both visual and textual information.
- Textual information can concern either the word or the sentence level.



# (visual-semantic) embeddings

- Multi-modal embeddings are created by
  - Fusion (**two-stage approach**)
    - Textual and visual features are extracted independently and then “combined”
  - Projection or joint learning (**one-stage approach**)
    - the model "learns" jointly by observing pairs (image, text)
    - representations related to different modalities are learned in a common multi-modal space
    - provides the model with multilayered information that can be transferred to images or texts it has never seen before

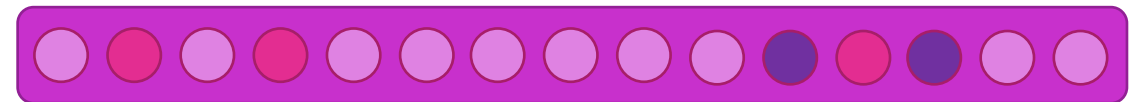
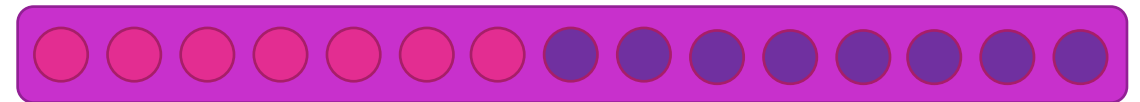


# (visual-semantic) embeddings

- Multi-modal embeddings encode both visual and textual information
- Textual information can be at both the word (e.g., object) and sentence (e.g., caption) levels



...  
a young tennis player preparing to  
serve a tennis **ball** to her opponent  
a tennis player leaps up to return the  
**ball**  
a tennis player is trying to hit a **ball**  
with a tennis racket  
...





# Problems and Tasks

# Vision-Language problems

- A first – broad – classification of multi-modal problems is between:
- Vision-Language **understanding** problems
  - a VL model to select the output from a given list of candidates
- Vision-Language **generation** problems
  - require a VL model to generate the output

# Multi-modal problems

- A multi-modal AI system should process such multi-modal data in an effective and efficient way.
- Following Gan et al., 2022, Vision-Language tasks can be grouped into three main categories:
  - Image-Text Tasks
  - Computer Vision Tasks as Vision-Language Problems
  - Video-Text Tasks

### VQA & Visual Reasoning

Q: What is the dog holding with its paws?  
A: Frisbee.

### Image Captioning

Caption: A dog is lying on the grass next to a frisbee.

### Text-to-Image Retrieval

Query: A dog is lying on the grass next to a frisbee.

#### Negative Images



### Text-to-Video Retrieval

Query: A dog is lying on the grass next to a frisbee, *while shaking its tail*.

#### Negative Videos

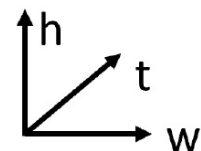


### Video Question Answering

Q: Is the dog perfectly still?  
A: No.

### Video Captioning

Caption: A dog is lying on the grass next to a frisbee, *while shaking its tail*.



### Image Classification

Labels: [dog, grass, frisbee]

### Object Detection



dog, grass, frisbee

### Segmentation



dog, grass, frisbee

Figure 1.2: Illustration of representative tasks from three categories of VL problems covered in this paper: image-text tasks, vision tasks as VL problems, and video-text tasks.

Image credit: Gan et al., 2022

# Image-Text Tasks

The most important and well-studied tasks in VL research are

- image-text retrieval
- image captioning (Vinyals et al., 2015)
- visual question answering (Antol et al., 2015)

## Image Captioning

Caption: A dog is lying on the grass next to a frisbee.

## VQA & Visual Reasoning

Q: What is the dog holding with its paws?  
A: Frisbee.

## Text-to-Image Retrieval

Query: A dog is lying on the grass next to a frisbee.

### Negative Images



...



# Image-Text Tasks: retrieval-related applications

- **Image-text retrieval.** The models are asked to retrieve the most relevant text (or image) from a large corpus, given the image (or text) query.
- **Visual grounding.** Instead of text outputs, requires bounding box outputs, where the model needs to predict the bounding box corresponding to the input text query.

# Image-Text Tasks: VQA-related applications

- VQA and visual reasoning models are asked to provide **open-ended free-form texts**, or **selecting an option** from multiple choices:
  - visual reasoning (Hudson and Manning, 2019b; Suhr et al., 2019)
  - visual commonsense reasoning (Zellers et al., 2019)
  - visual dialog (Das et al., 2017)
  - knowledge-based VQA (Marino et al., 2019)
  - scene-text-based VQA (Singh et al., 2019).



# Image-Text Tasks: Captioning-related applications

- The typical setting in captioning is generating a short sentence (Lin et al., 2014)
- Related tasks include:
  - image **paragraph** captioning (Krause et al., 2017)
  - **scene-text-based** image captioning (Sidorov et al., 2020)
  - visual **storytelling** (Huang et al., 2016)
- **Text-to-image generation** is a dual task of image captioning: the system is required to **create an image based on the text input**.

# “Aided” Computer Vision Tasks

- **Core vision problems** such as image classification, object detection, and segmentation **benefit of language supervision**.
- Instead of treating the supervision signals (e.g., class labels) as one-hot vectors, the **semantic meaning of the labels** is exploited to generalize the traditional close-set classification or detection models to recognizing **unseen concepts** (i.e., open-vocabulary object detection).

## Image Classification

Labels: [dog, grass, frisbee]

### Object Detection



dog, grass, frisbee

### Segmentation



dog, grass, frisbee

# Video-Text Tasks

- All aforementioned image-text tasks have their video-text counterparts, such as video captioning, retrieval, and question answering.
- AI systems are not only asked to capture **spatial information** within a single video frame, but also the **temporal dependencies** among frames.

## Text-to-Video Retrieval

Query: A dog is lying on the grass next to a frisbee, *while shaking its tail*.

## Negative Videos



## Video Question Answering

Q: Is the dog perfectly still?

A: No.

## Video Captioning

Caption: A dog is lying on the grass next to a frisbee, *while shaking its tail*.



# Multi-modal datasets

# Multi-modal datasets

- Vision-language models are pre-trained on large multi-modal datasets.
- Text data typically include **human-generated captions**, object labels, image metadata and other **information relevant for specific tasks** (e.g., questions and answers).

# Trends on multi-modal data

We focus on general-purpose datasets for Vision-Language Models!

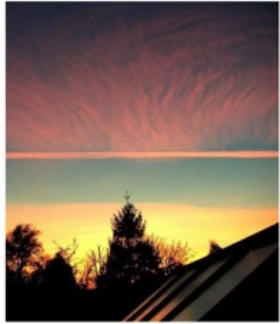
- **Pioneering** multi-modal datasets were designed for training a model on **specific tasks** such as captioning, VQA, object detection etc.
- Nowadays, following the trend observed for Large Language Models VL models are typically:
  - **pre-trained** on a vast number of multi-modal data
  - and then **fine-tuned** (or used under a **zero / few shot setting**)

# Pioneering multi-modal datasets

- SBU Captions (Ordonez et al., 2011), Conceptual Captions, CC3M (Sharma et al., 2018) and Flickr30K (Young et al., 2014): **captioning datasets**
  - datasets scraped from the web with accompanying captions
- COCO (Chen et al., 2015) : **object detection** and **image captioning**
  - consists of image instances with object labels and natural sentence descriptions.
- Visual Genome, VG (Krishna et al., 2017): **object detection, region descriptions** and **relationships, questions & answers**
  - contains objects, attributes, and relationships within each image



# SBU Captions, Conceptual Captions and Flickr30K



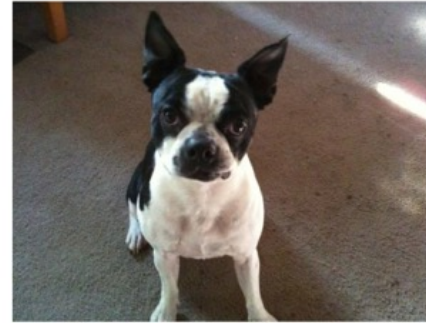
Amazing colours in the sky at sunset with the orange of the cloud and the blue of the sky behind.



A female mallard duck in the lake at Luukki Espoo



Fresh fruit and vegetables at the market in Port Louis Mauritius.



Street dog in Lijiang



Tree with red leaves in the field in autumn.



One monkey on the tree in the Ourika Valley Morocco



Clock tower against the sky.



The river running through town I cross over this to get to the train



Strange cloud formation literally flowing through the sky like a river in relation to the other clouds out there.



The sun was coming through the trees while I was sitting in my chair by the river



# SBU Captions, Conceptual Captions and Flickr30K



**Alt-text:** A Pakistani worker helps to clear the debris from the Taj Mahal Hotel November 7, 2005 in Balakot, Pakistan.

**Conceptual Captions:** a worker helps to clear the debris.



**Alt-text:** Musician Justin Timberlake performs at the 2017 Pilgrimage Music & Cultural Festival on September 23, 2017 in Franklin, Tennessee.

**Conceptual Captions:** pop artist performs at the festival in a city.

# SBU Captions, Conceptual Captions and Flickr30K



*Gray haired man in black suit and yellow tie working in a financial environment.*  
*A graying man in a suit is perplexed at a business meeting.*  
*A businessman in a yellow tie gives a frustrated look.*  
*A man in a yellow tie is rubbing the back of his neck.*  
*A man with a yellow tie looks concerned.*



*A butcher cutting an animal to sell.*  
*A green-shirted man with a butcher's apron uses a knife to carve out the hanging carcass of a cow.*  
*A man at work, butchering a cow.*  
*A man in a green t-shirt and long tan apron hacks apart the carcass of a cow while another man hoses away the blood.*  
*Two men work in a butcher shop; one cuts the meat from a butchered cow, while the other hoses the floor.*



# COCO



## Captions (5)

a blue bike parked on a side walk  
a bicycle is chained to a fixture on a city street  
a blue bicycle sits on a sidewalk near a street.  
a bicycle is locked up to a post  
a bike sits parked next to a street

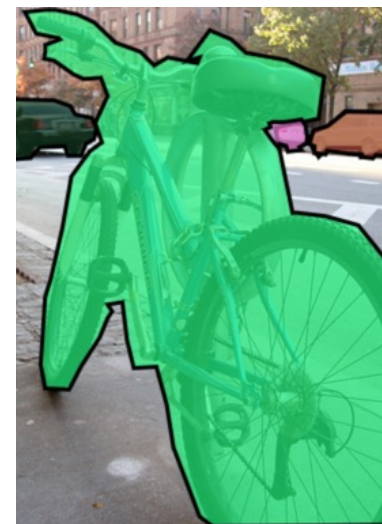
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## Objects

19765 traffic light  
19766 traffic light  
19767 traffic light  
20403 bicycle  
20896 car  
20897 car  
20898 car  
20899 car  
20900 car  
22828 truck  
22829 truck  
22830 truck



## Segmentation



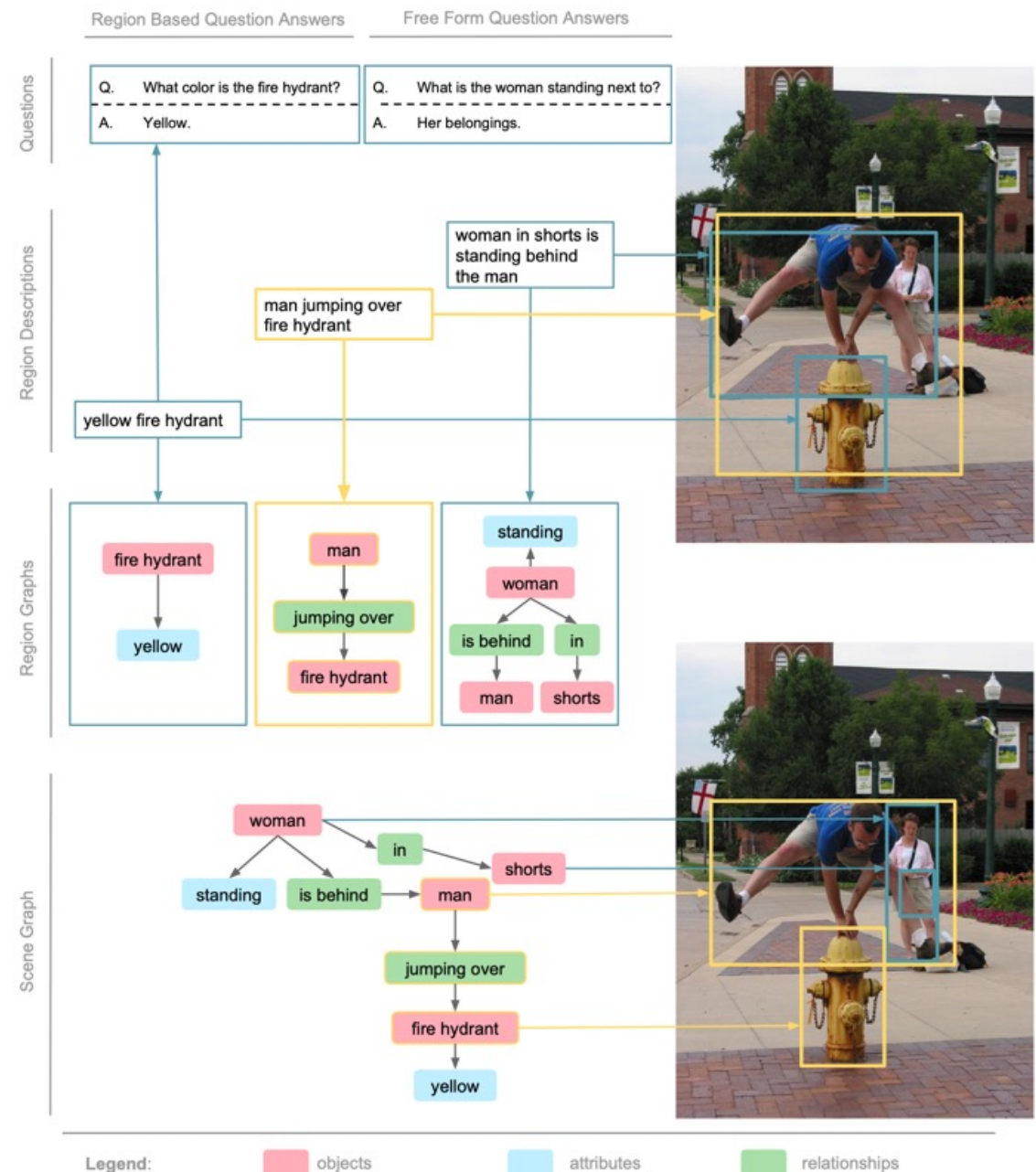
## Key points



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# Visual Genome (VG)

- **scene graphs contain:**
  - images
  - objects (provided with synsets)
  - relations (provided with synsets)
  - region descriptions
  - (in natural language)
  - questions & answers



# Visual Genome (VG)

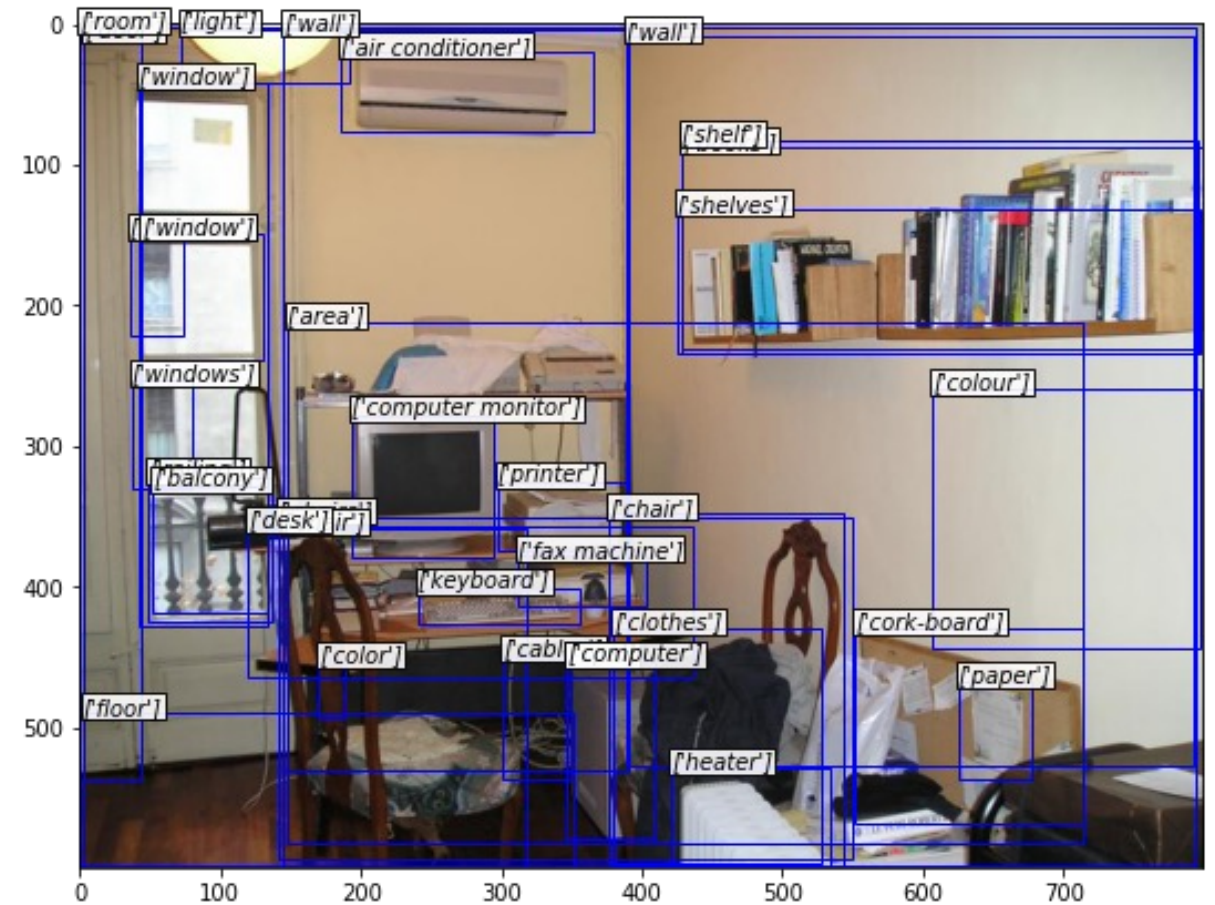
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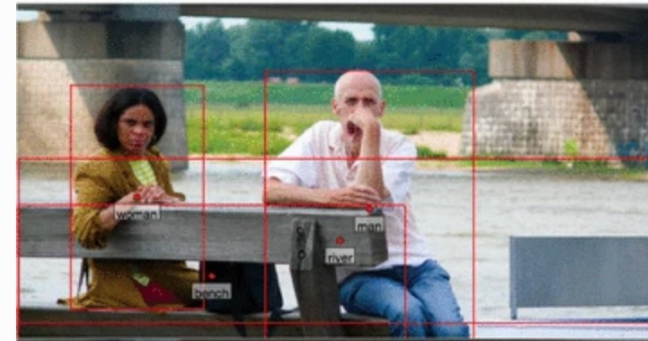
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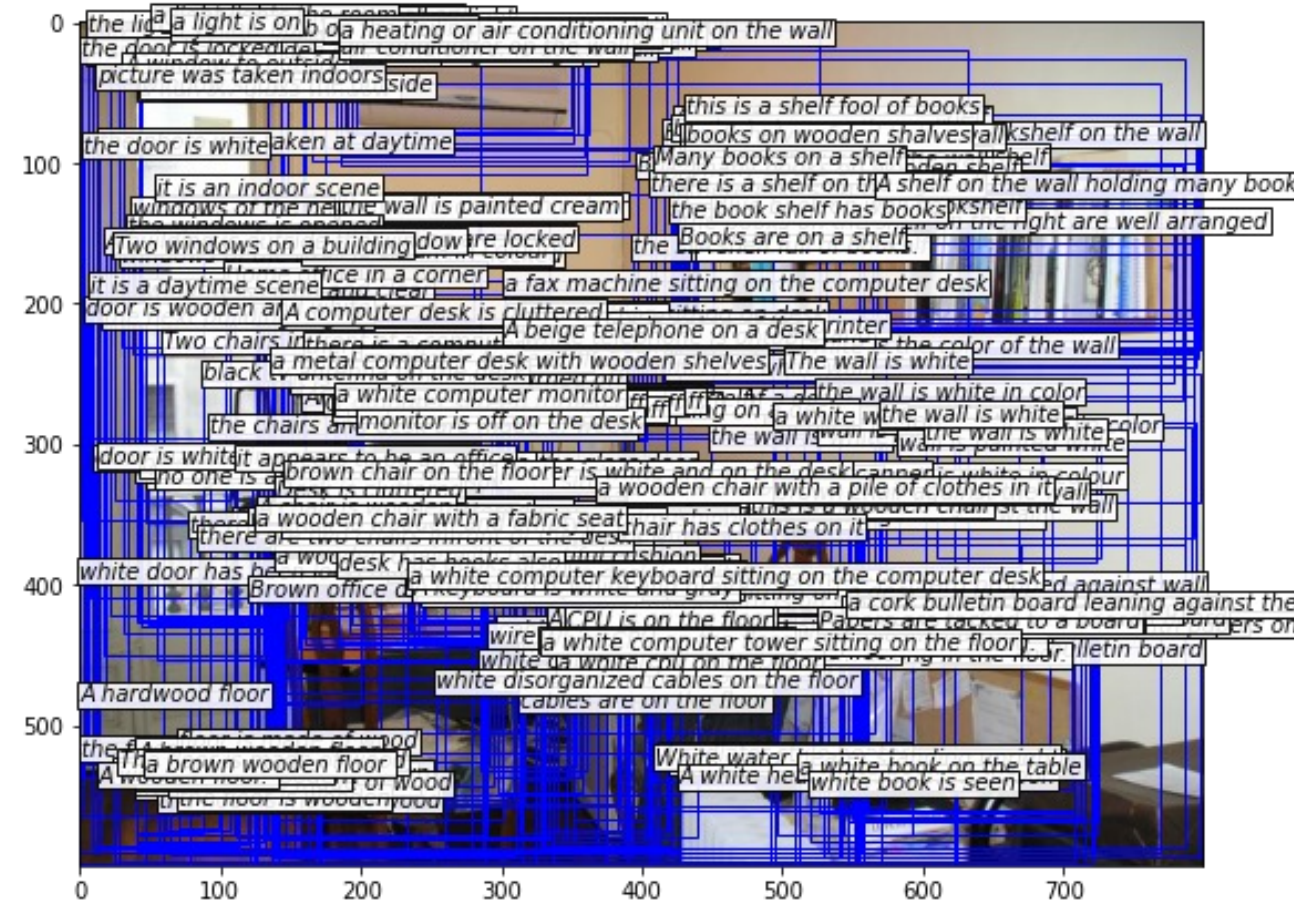


A man and a woman sit on a park bench along a river.

```
... {'synsets': ['along.r.01'], 'predicate': 'ON', 'relationship_id': 3187870,
    'object_id': 1060360, 'subject_id': 1060364}, {'synsets': ['along.r.01'],
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    'object_id': 1060351, 'subject_id': 1060375}, {'synsets': ['earlier.r.01'],
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    'relationship_id': 3187880, 'object_id': 1060360, 'subject_id': 1060371} ...
```

# Visual Genome (VG)

- **scene graphs contain:**
  - images
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  - relations (provided with synsets)
  - **region descriptions**  
**(in natural language)**
  - questions & answers





# Visual Genome (VG)

- **scene graphs contain:**
  - images
  - objects (provided with synsets)
  - relations (provided with synsets)
  - region descriptions  
(in natural language)
  - **questions & answers**

# Visual Genome (VG)

**object detection**



**Q:** How many people are wearing a lettered, zip-up red jacket?  
**A:** Just one.

**object attributes**



**Q:** What is the most valuable device in this room?  
**A:** The television.

**object classification**



**Q:** What animal is the balloon modelled after?  
**A:** Blue whale.

**scene classification**



**Q:** Where was the picture taken?  
**A:** At the beach.

**fine-grained recognition**



**Q:** What kind of boat is the far left blue boat?  
**A:** Sail boat.

**action recognition**



**Q:** What is the snowboarder doing?  
**A:** Jumping.

**text detection**



**Q:** When was the bridge built?  
**A:** 1932.

**spatial reasoning**



**Q:** Where is the American flag?  
**A:** Behind president Reagan.

**event understanding**



**Q:** What holiday is being celebrated?  
**A:** Fourth of July.

**common sense**



**Q:** Why is the man's tie moving?  
**A:** The wind is blowing.

**person identification**



**Q:** Who is this man?  
**A:** Derek Jeter.

**facial expressions**



**Q:** What expression is on most people's faces?  
**A:** They are smiling.

# The era of Large Vision-Language Models

- Vision-language models are trained on image and text datasets with different structures on the pre-training objective.
- Pre-trained models are fine-tuned on downstream tasks with task-specific datasets.

# Pre-Training Datasets

- In a **typical academic setting**, VL models are pre-trained on a collection of four commonly used image-caption datasets:
  - COCO (Chen et al., 2015)
  - Visual Genome (VG) (Krishna et al., 2017)
  - Conceptual Captions (CC<sub>3</sub>M) (Sharma et al., 2018)
  - SBU Captions (Ordonez et al., 2011)

# Pre-Training Datasets

- In a **typical industrial setting**, datasets are **large scale** and **web-crawled**. Most of them are proprietary. Some of them are:
  - The dataset used in CLIP (Radford et al., 2021) consists of 400 M image-text pairs, PROPRIETARY
  - The dataset used in ALIGN (Jia et al., 2021) has 1.8 B image-text pairs, PROPRIETARY
  - The dataset used in Florence (Yuan et al., 2021) and GIT (Wang et al., 2022d) contains 800 M image-text pairs, PROPRIETARY
  - WenLan (Huo et al., 2021) consists of 30 million image-text pairs (web-collected exploiting topic models, elaborate cleaning process), PROPRIETARY

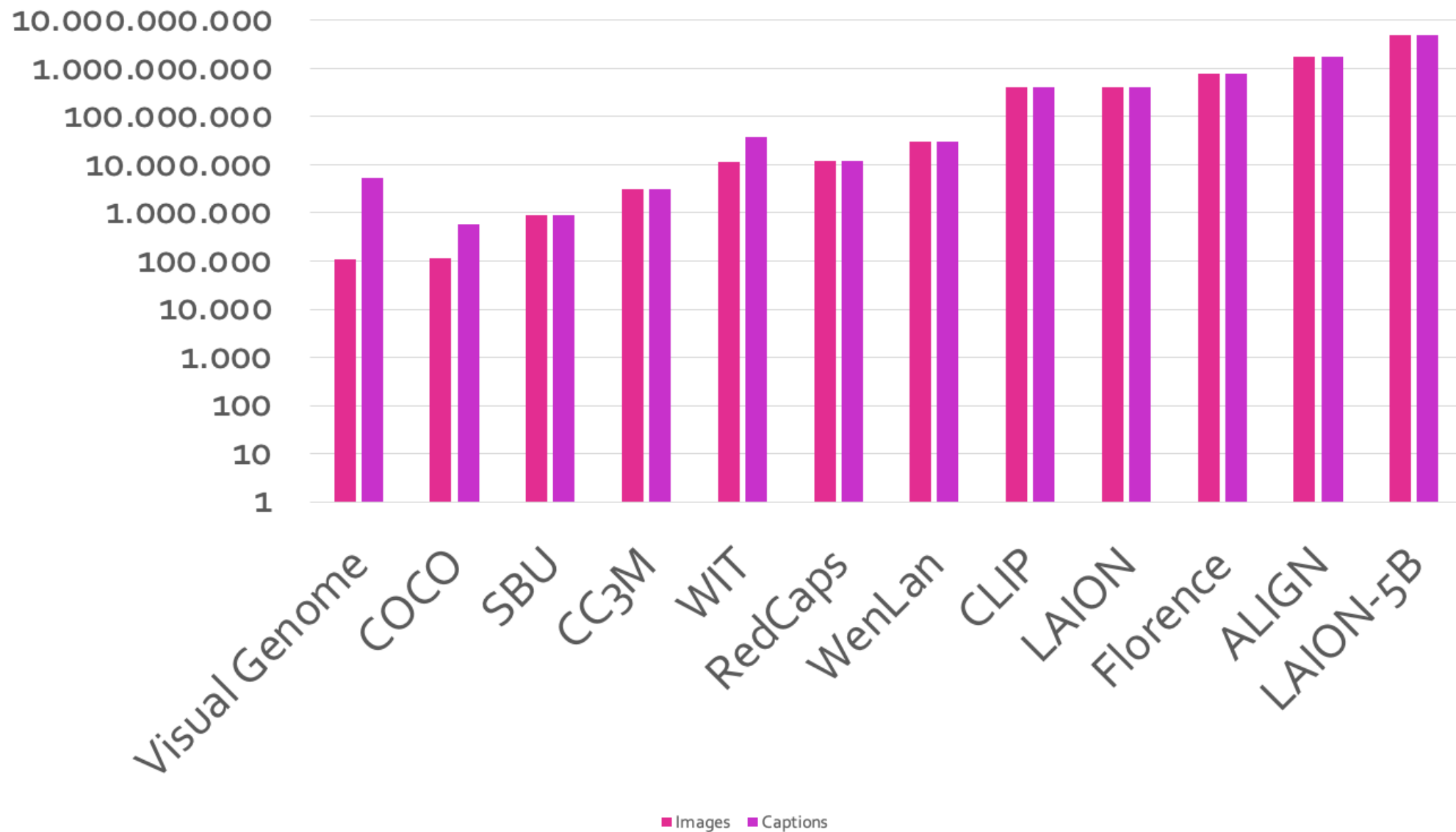
# Pre-Training Datasets

- In a **typical industrial setting**, datasets are **large scale** and **web-crawled**.

Most of them are proprietary. Some of them are:

- LAION-400M/5B (Schuhmann et al., 2021) has 400 M or 5 B image-text pairs, PUBLIC
- RedCaps (Desai et al., 2021) includes 12 M image-text pairs (subreddits), PUBLIC
- The Wikipedia-based Image-Text Dataset (WIT) (Srinivasan et al., 2021) is composed of 11.5 M unique images and 37.6 M texts (multilingual, across 108 languages), PUBLIC

## Dataset size (log scale!)



+ •  
Case study:  
**The COCO dataset**



# Exploring COCO

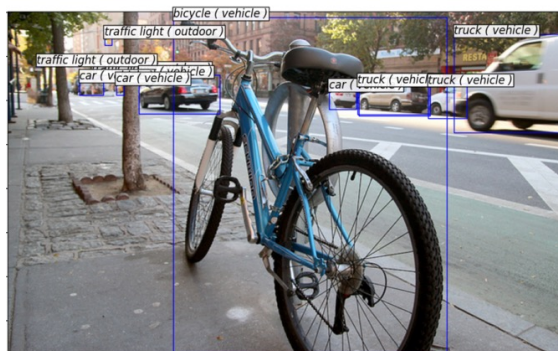


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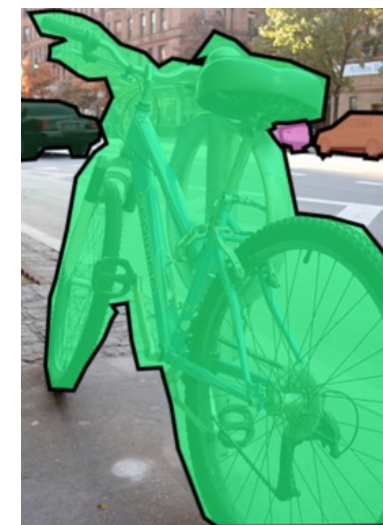
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Notebook:  
[Exploring COCO  
data from scratch!](#)

## Segmentation





## Datasets and models



**Hugging Face**



# Hugging Face

A **community** and data science **platform** offering:

- **Advanced Tools:** Empowering users to create, train, and deploy machine learning models using open-source code and technologies.
- **Collaborative Space:** A platform that brings together a diverse community of data scientists, researchers, and ML engineers to exchange ideas, receive support, and actively contribute to open-source projects.

# ... for our purposes

- Hugging Face is very useful for accessing available
  - Pre-Trained (multi-modal) **models**
    - Both **foundational** and **specialized** on tasks
  - **Datasets**
    - With a common data format, ready to be used with the pre-trained models

# Hugging Face Datasets

- A library for accessing and sharing **datasets** (Text, Audio, Vision, Multi-modal)
  - **Integrated** with the Hugging Face Hub
- Datasets can be easily loaded
  - single line of code
- Apache Arrow format
  - enables large amounts of data to be processed and moved quickly
  - language-agnostic, column-oriented, supported by ML tools
  - stores data in a columnar memory layout (many, possibly nested, column types)

Notebook:  
[The COCO Dataset  
in HuggingFace](#)

# Hugging Face Pipelines

- Using the pipelines is the simplest way to use **pretrained models** for inference.
- Both existing models (available in huggingface) and to your own can be used.
- They deal with both **uni-modal** and **multi-modal tasks**.
- A pipeline is a wrapper built for working around all the other available pipelines.

It can be executed on:

- a single item
- a list of items (list)
- a Dataset

Notebook:  
[Using Hugging Face  
Pipelines for inference](#)

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*Notebooks and Slides here +*



# THANK YOU FOR YOUR ATTENTION





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