

CATEGORY THEORY COURSE NOTES

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INTRODUCTION

These are course notes from the winter 2024 semester Category Theory course at Dalhousie university taught by Dorette Pronk. We follow Robin's notes [?] with occasional reference to Emily Riehl's book [?]. She gave us options to do seminar-style presentations or guest lectures to replace exams.

Categories are a lot of things to a lot of people. They are places where mathematical objects are studied by structure preserving morphisms between them that satisfy some composition laws. Like the mathematical objects they so often contextualize, categories can be studied in terms of structure preserving morphisms between them in a 'higher' categorical context! We'll get there eventually.

We begin with some familiar examples of (concrete) categories and check out some of the formal structures and properties they have, but first...

A BIT OF HISTORY

This little summary is from Dorette's slides from her honours talk in Feb 2020. Category theory was developed for a couple of reasons. One was to contextualize the mathematical objects people cared about and study them in terms of their morphisms (Emmy Noether started this idea) and another was the idea of 'natural' operations that we could perform on such objects. For example, functions between groups should preserve the group structure in order to be considered morphisms of groups and the isomorphisms between finite dimensional vector spaces and their duals depending on a chosen basis are instances of these ideas showing up.

Category theory was particularly important in (re)developing the foundations of algebraic topology. Euler characteristic was the first known result of a 'topological invariant.' Riemann studied connectivity of complex varieties (zero sets of polynomial equations); for example disconnecting a sphere can be done with one circle and disconnecting a torus requires at least two. Möbius strips were a first instance of studying orientability of surfaces. Betti numbers were inspired by Riemann's connectivity of surfaces to quantify connectivity in higher dimensions using higher dimensional spheres and boundary relations. Poincaré studies solutions to differential equations on algebraic varieties and found Betti numbers played an important role in these questions; he introduced torsion coefficients to capture the monodromy. Nowadays we see Betti numbers as ranks of abelian groups that show up in the study of what we now know as (singular) homology.

Emmy Noether was the first to suggest studying the algebraic complexes associated to spaces, specifically we should study the 'holes' in a complex directly as the equivalence classes of cycles in the complex modulo their boundaries. This also led to Alexandrov's theory of 'continuous decompositions' which is essentially the perspective of (the image of) a continuous map as a bundle of fibers above points in its codomain. Homology doesn't intertwine the group structure and the topological structure, it relates continuous maps with group homomorphisms. I'll ask for a link to her slides, anyway category theory will help us contextualize relationships between mathematical objects and state and prove more precise statements about them.

1. JAN 8TH

A category is an abstract setting where *composition* makes sense.

Definition 1. A category is a directed multigraph, $(\mathcal{C}_0, \mathcal{C}_1)$ along with an associative and unital algebra of paths.

The directed multigraph tells you what the ‘objects’ and ‘arrows’ are and the algebra of paths says arrows whose domain and codomain agree can be composed. The objects of \mathcal{C} are denoted \mathcal{C}_0 and the arrows are denoted \mathcal{C}_1 . Let $d_0 : \mathcal{C}_1 \rightarrow \mathcal{C}_0$ denote the function that picks out the domain of an arrow and $d_1 : \mathcal{C}_1 \rightarrow \mathcal{C}_0$ the function that picks out the codomain. The path algebra says that for any $f, g \in \mathcal{C}_1$, if $d_1(f) = d_0(g)$ then there exists a unique composite $g \circ f \in \mathcal{C}_1$ whose domain and codomain agree with those of f and g respectively:



Associativity of the path algebra encodes associativity of arrow composition in the category \mathcal{C} .

$$h \circ (g \circ f) = (h \circ g) \circ f,$$

The constant paths in the path algebra correspond to identity arrows, $1_A : A \rightarrow A$, and satisfy an identity law,

$$1_B \circ f = f = f \circ 1_A$$

for any $f : A \rightarrow B$.

Examples. Here are a bunch of examples you can verify yourself. To show something is a category you need to check there are well-defined objects, arrows, composition, identities, and that identity and associativity laws for composition hold.

- (a) The category of sets and functions is a category with function composition.
- (b) The category of groups and group homomorphisms is a category again with function composition.
- (c) Vaguely but more generally speaking the category of (algebraic thing) with (algebraic thing) homomorphisms is a category. There’s a way to talk about these kinds of ‘algebraic theories’ more generally that we’ll encounter later in the course!
- (d) Any directed multigraph can be made into a category by freely adding finite paths and identities.
- (e) The small categories \mathbb{K} and \mathbb{K}^* have as many objects and one less non-identity arrow. The first one is pictured below:

$$A \curvearrowright$$

- (f) The category of topological spaces and continuous maps between them is a category.
- (g) Any set with a pre-order defines a category whose objects are the elements of the set and whose arrows are determined by the pre-order relation.
- (h) If \mathcal{C} is a category and $X \in \mathcal{C}_0$ is an object, the *slice category over X*, \mathcal{C}/X , has arrows in \mathcal{C} with codomain X as its objects and commuting triangles (over X) in \mathcal{C} as its arrows. Composition and identities are inherited from \mathcal{C} .

1.1. **January 12th.** I missed this class for a tennis tournament, we wrote down some definitions and talked about the path category associated to a directed (multi)graph. We talked about **Rel** and **Par** as further examples.

1.2. **January 15th.**

Definition 2. The *dual* of a category \mathcal{C} is denoted \mathcal{C}^{op} . It has the same objects as \mathcal{C} and the arrows are determined by those in \mathcal{C} but are written in the opposite direction:

$$\mathcal{C}^{op}(A, B) = \mathcal{C}(B, A)$$

Examples. (1) Check that \mathcal{C}^{op} is in fact a category.

(2) The category **Rel** is isomorphic to its opposite, **Rel**^{op}.

(3) The category **Mat**(**R**) has natural numbers as objects and arrows $m \rightarrow n$ are $n \times m$ -matrices with coefficients in the ring R . Composition is matrix multiplication and identities are the identity matrices.

Now that we have some examples of categories, let's look at some properties that arrows in a category may have.

Definition 3. An arrow $f : A \rightarrow B$ is a *monomorphism* if $g \circ f = h \circ f$ implies $g = h$. In pictures, if the diagram

$$A \xrightarrow{f} B \begin{array}{c} \xrightarrow{g} \\ \xrightarrow{h} \end{array} C$$

commutes, then $g = h$.

Examples. What are the monomorphisms in **Set**? **Grp**? **Rel**?

The dual notion of a monomorphism is an epimorphism. It can be defined as a monomorphism in the opposite category or that result can be proven from the following definition:

Definition 4. An arrow $f : A \rightarrow B$ is an *epimorphism* if $f \circ g = f \circ h$ implies $g = h$. In pictures, if the diagram

$$C \begin{array}{c} \xrightarrow{g} \\ \xrightarrow{h} \end{array} A \xrightarrow{f} B$$

commutes, then $g = h$.

Examples. What are the epimorphisms in **Set**? **Grp**? **Rel**?

Proposition 5. The mono/epimorphisms in \mathcal{C} are precisely the epi/monomorphisms in \mathcal{C}^{op} respectively.

Definition 6. An arrow with a left (post-compositional) inverse is called a *retraction* and an arrow with a right (pre-compositional) inverse is called a *section*.

Examples. An *inverse* of an arrow is a left and a right inverse. Show that such an arrow is necessarily unique.

Definition 7. An *isomorphism* is an arrow with a left and right inverse.

Examples. Find or construct a category with at least one arrow that's monic and epic but not an isomorphism.

Lemma 8. If $g \circ f$ is monic then f is monic and if $g \circ f$ is epic then g is epic.

Solution. These are dual statements, it suffices to prove one. □

Lemma 9. *The following are equivalent:*

- (a) *The map $f : A \rightarrow B$ is an isomorphism.*
- (b) *f is an epic section*
- (c) *f is a monic retraction*

Solution. □

Definition 10. A *subobject* is an equivalence class of monomorphisms with a common codomain. Two mono's with a common codomain represent the same subobject if they're isomorphic in the slice category over that codomain.

Definition 11. An *idempotent* is an arrow $e : A \rightarrow A$ such that $e^2 = e$.

Dorette thinks about these as ‘really nice subobjects.’ We’ll hear about why next class when we talk about partially defined maps a bit more.

1.3. January 17th.

Examples. Let $r : A \rightarrow B$ be a retraction of $s : B \rightarrow A$, a section. Then $r \circ s = 1$ implies $(s \circ r)^2 = s \circ r$ is idempotent.

Not every subobject gives an idempotent because there may not be a projection onto that subobject; equivalently: not every projection has a global section. Idempotents that can be given this way are called *split idempotents*. In **Set** for example, every idempotent $e : X \rightarrow X$ splits, via its image, as a retraction followed by a section:

$$\begin{array}{ccc} X & \xrightarrow{e} & X \\ & \searrow r_e & \nearrow s_e \\ & \text{ime} & \end{array}$$

where r_e is just e with a restricted codomain and s_e is subset inclusion.

Proposition 12. *Idempotent splittings are unique in the sense that for any two splittings $e = s \circ r$ and $e = r' \circ s'$ of an idempotent e there exists a unique isomorphism $h : \text{doms} \rightarrow \text{doms}'$ such that $h \circ r = r'$ and $s' \circ h = s$.*

Solution. Define $h = r' \circ s$ and check that everything works. The inverse is $h^{-1} = r \circ s'$. □

Corollary 13. *Split idempotents correspond to subobjects.*

Definition 14. The universal way to split idempotents in a category \mathcal{C} is called the ‘Karoubi envelope.’ This is a new category whose objects are the idempotents in \mathcal{C} and whose arrows $f : e_1 \rightarrow e_2$ are given by arrows $f : \text{dome}_1 \rightarrow \text{dome}_2$ in \mathcal{C} such that $e_2 \circ f \circ e_1 = f$ so the diagram

$$\begin{array}{ccc} A & \xrightarrow{e_1} & A \\ f \downarrow & \searrow f & \downarrow f \\ B & \xrightarrow{e_2} & B \end{array}$$

Composition is given by stacking commuting squares

$$\begin{array}{ccc}
 A & \xrightarrow{e_1} & A \\
 f \downarrow & \searrow f & \downarrow f \\
 B & \xrightarrow{e_2} & B \\
 g \downarrow & \searrow g & \downarrow g \\
 C & \xrightarrow{e_3} & C
 \end{array}
 =
 \begin{array}{ccc}
 A & \xrightarrow{e_1} & A \\
 g \circ f \downarrow & \searrow g \circ f & \downarrow g \circ f \\
 C & \xrightarrow{e_3} & C
 \end{array}$$

and the identity arrow on e is e .

$$\begin{array}{ccc}
 A & \xrightarrow{e} & A \\
 e \downarrow & \searrow e & \downarrow e \\
 A & \xrightarrow{e} & A
 \end{array}$$

Examples. For the category of open subsets of \mathbb{R}^n and the smooth functions between them, the Karoubi envelope is the category of (smooth) manifolds. This relies on the tubular neighborhood theorem for manifolds (that you can embed them in \mathbb{R}^n and thicken them with an interval to get an open subset of \mathbb{R}^n).

In a similar fashion, vector bundles form the karoubi envelope of the category of trivial bundles.

The original category \mathcal{C} embeds into the Karoubi envelope:

$$\mathcal{C} \rightarrow \text{Kar}(\mathcal{C})$$

by sending each object to its identity map and arrows to the obvious squares. Notice this assignment preserves the ‘category structure,’ namely identities and composition.

Split epimorphisms are examples of arrows that factor in a universal way as a composite of arrows from two special classes of arrows. A factorization system in a category describes when every arrow factors as a composite of two arrows from two special classes of arrows. An example of a factorization system in **Set** is the epi-mono factorization which comes from noticing that every function $f : A \rightarrow B$ factors as an epimorphism (given by restricting its codomain to the image) followed by a monomorphism (given by including the image as a subset).

Definition 15. Let $\mathcal{E}, \mathcal{M} \subseteq \mathcal{C}_1$ be two classes of arrows that are closed under composition and both containing the identity arrows. Then \mathcal{C} has an \mathcal{E} - \mathcal{M} factorization system if every arrow in \mathcal{C} factors as a composite of an arrow in \mathcal{E} followed by an arrow in \mathcal{M} and this factorization is unique up to a unique map between the intermediate objects. We write arrows in \mathcal{E} with two heads and arrows in \mathcal{M} with tails, the universal property looks like:

$$\begin{array}{ccccc}
 & & X & & \\
 & \nearrow & & \searrow & \\
 A & \xrightarrow{\cong} & & \xrightarrow{f} & B \\
 & \searrow & & \nearrow & \\
 & & Y & &
 \end{array}$$

1.4. **January 9th.** Today we start with the notion of orthogonality (of arrows in a category).

Definition 16. Let $f : A \rightarrow B$ and $g : C \rightarrow D$ be two arrows in a category \mathcal{C} . We say ‘ f is *left orthogonal* to g ’ or ‘ g is *right orthogonal* to f ,’ and we write $f \perp g$ if every commutative diagram

$$\begin{array}{ccc} A & \xrightarrow{h_1} & C \\ f \downarrow & & \downarrow g \\ B & \xrightarrow{h_2} & D \end{array}$$

has a unique filler

$$\begin{array}{ccc} A & \xrightarrow{h_1} & C \\ f \downarrow & \nearrow k & \downarrow g \\ B & \xrightarrow{h_2} & D \end{array}$$

making each of the triangles commute.

Remark. If $f \perp g$ in \mathcal{C} then $g^{op} \perp f^{op}$ in \mathcal{C}^{op} .

Examples.

- (a) Every epimorphism is left orthogonal to every monomorphism in **Set**.
- (b) For $f : \{0, 1\} \rightarrow \{*\}$ the right orthogonal arrows are functions with singleton fibers. This is required to ensure uniqueness of the filler since $h_1 : \{0, 1\} \rightarrow C$ is able to separate points in \mathcal{C} and having singleton fibers is another way to say the function is injective.

We say f is *weakly* orthogonal to g if the filler, k , in Definition 16 exists but is not unique.

Examples.

- (a) For $\emptyset \rightarrow \{*\}$ (in **Set**), the weakly right orthogonal arrows are the surjective functions. The (strictly) right orthogonal arrows are the bijections. To see why, ask yourself ‘what do the fibers of such a map have to be?’
- (b) In **Top**, the weakly right orthogonal maps to the inclusion $\{0\} \hookrightarrow [0, 1]$ are those that have the path lifting property with respect to that inclusion. This class includes the covering maps but it also contains more!
- (c)

1.5. **January 22nd.** We have seen that in **Set** all epi’s are left orthogonal to all mono’s. In **Set**, mono’s are also weakly left orthogonal to epi’s.

Definition 17. Let $\mathcal{E}, \mathcal{M} \subseteq \mathcal{C}_1$ be two classes of arrows in \mathcal{C} . We say \mathcal{E} is left orthogonal to \mathcal{M} if every arrow in \mathcal{E} is left orthogonal to every arrow in \mathcal{M} .

What if we want to add stuff into \mathcal{E} and \mathcal{M} ?

Definition 18. The class of arrows that are right orthogonal to all arrows in \mathcal{E} is denoted \mathcal{E}_\perp . The class of arrows that are left orthogonal to all arrows in \mathcal{M} are denoted ${}_\perp\mathcal{M}$.

Proposition 19. For any class of arrows \mathcal{E} we have that \mathcal{E}_\perp contains all iso’s, ${}_\perp(\mathcal{E}_\perp) \supseteq \mathcal{E}$.

Solution.

□

Proposition 20. The class of arrows left orthogonal to the class of isomorphisms is all of the arrows: ${}_\perp Iso = \mathcal{C}_1$.

Proposition 21. *Claim— $(\perp(\mathcal{E}_\perp))_\perp = \mathcal{E}_\perp$*

Solution. Suppose $A \subseteq A'$, then $A_\perp \supseteq A'_\perp$ and $\perp A \supseteq \perp A'$ so that

$$A \subseteq_\perp (A_\perp).$$

Applying \perp once more on the right we get

$$A_\perp \supseteq (\perp(A_\perp))_\perp$$

and also we have $(\perp(A_\perp))_\perp \supseteq A_\perp$. This shows both subset inclusions and the equality follows. \square

Proposition 22. *For any class of arrows A there are two maximal classes of arrows A_1 and A_2 such that $(A_1)_\perp = A_2$ and $\perp(A_2) = A_1$ and $A_1 \supseteq A$.*

Solution. Let $A_1 = \perp(A_\perp)$ and let $A_2 = A_\perp$. \square

Lemma 23. *Let $A \subseteq \mathcal{C}_1$ be a class of arrows.*

- (1) *Isomorphisms are right (and left) orthogonal to A .*
- (2) *If $x \in A \cap A_\perp$ then x is an iso.*
- (3) *A_\perp and $\perp A$ are closed under composition.*
- (4) *If $h \circ g \in A_\perp$ and h is monic then $g \in A_\perp$. Is the dual statement: if $g \circ h \in \perp A$ and g is epic then $h \in \perp A$?*
- (5) *If $h \circ g \in A_\perp$ and $h \in A_\perp$ then $g \in A_\perp$. Write down the dual statement.*

Solution. Exercise in diagram chasing and unraveling definitions. \square

Definition 24. A factorization system in a category \mathcal{C} is a pair $(\mathcal{E}, \mathcal{M})$ of classes of arrows $\mathcal{E}, \mathcal{M} \subseteq \mathcal{C}_1$ such that \mathcal{E} and \mathcal{M} contain all iso's, \mathcal{E} and \mathcal{M} are closed under composition, and every map f factors as $f = g \circ h$ where $h \in \mathcal{E}$ and $g \in \mathcal{M}$ uniquely up to a unique isomorphism (between the mediating object(s) in the middle).

1.6. January 24th.

Proposition 25. *If $(\mathcal{E}, \mathcal{M})$ is a factorization system in \mathcal{C} then*

- (a) *\mathcal{E} is left orthogonal to $c\mathcal{M}$*
- (b) *Factorizations extend to commutative squares.*

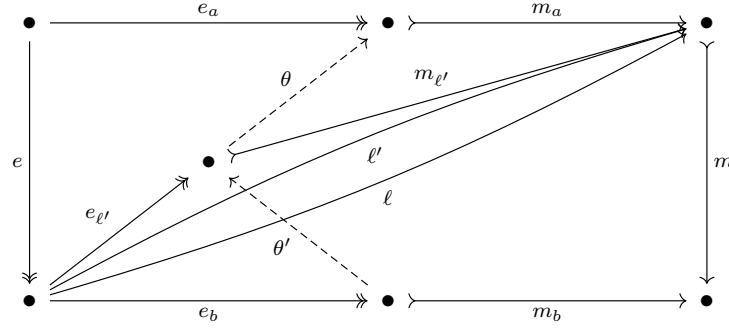
Solution. Consider the lifting problem:

$$\begin{array}{ccc} A & \xrightarrow{a} & A' \\ e \downarrow & & \downarrow m \\ B & \xrightarrow{b} & B' \end{array}$$

where the two headed arrow is in \mathcal{E} and the arrow with a tail is in \mathcal{M} . We factor both the top and bottom arrows and obtain a filler by uniqueness of factorizations:

$$\begin{array}{ccccc} A & \xrightarrow{e_a} & E_A & \xrightarrow{m_a} & A' \\ e \downarrow & & \uparrow k & & \downarrow m \\ B & \xrightarrow{e_b} & E_B & \xrightarrow{m_b} & B' \end{array}$$

Notice $\ell = m_a \circ k \circ e_b$ solve the lifting problem. To see this solution is unique suppose there's another solution ℓ' and factor it



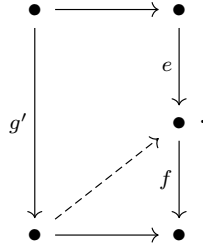
By uniqueness we have $\theta \circ \theta' = k$ and consequently $\ell = \ell'$:

$$\begin{aligned}
 \ell &= m_a \circ k \circ e_b \\
 &= m_a \circ \theta \circ \theta' \circ e_b \\
 &= m_{\ell'} \circ \theta \circ e_b \\
 &= m_{\ell'} \circ e_{\ell'} \\
 &= \ell'.
 \end{aligned}$$

It follows that the lift ℓ is unique.

Factor the vertical arrows in a commuting square, squish it into a (rectangular) lifting problem that can be uniquely solved. □

Definition 26. Given a class \mathcal{E} of maps we say that an arrow f in \mathcal{C} has a maximal \mathcal{E} -factorization if it can be factors as $f = f' \circ e$ with $e \in \mathcal{E}$ such that for all commutative squares there exists a unique filler as in the diagram below:



We say \mathcal{C} has a maximal \mathcal{E} -factorization if every arrow in \mathcal{C} has a maximal \mathcal{E} -factorization.

The dual concept is a *maximal \mathcal{M} -cofactorization system*.

Proposition 27. *The following are equivalent:*

- (1) *There are two classes \mathcal{E} and \mathcal{M} such that*
 - \mathcal{E} *is left orthogonal to* \mathcal{M}
 - \mathcal{E} *is closed under (post-)composition with iso's.*
 - \mathcal{M} *is closed under (pre-)composition with iso's.*
 - Each map f can be factored as $f = m \circ e$ for $e \in \mathcal{E}$ and $m \in \mathcal{M}$.*
- (2) *$(\mathcal{E}, \mathcal{M})$ is a pair of maximal orthogonal classes of maps such that every map in \mathcal{C} factors as $m \circ e$ for some $m \in \mathcal{M}$ and $e \in \mathcal{E}$.*
- (3) *\mathcal{E} is a class of maps containing all iso's and closed under composition such that each map $f \in \mathcal{C}$ can be factored as a maximal \mathcal{E} -factorization*

- (4) \mathcal{M} is a class of maps closed under composition and containing all iso's such that every map factors as a maximal \mathcal{M} -factorization. (dual to the previous one)
- (5) $(\mathcal{E}, \mathcal{M})$ is a factorization system.

Solution. Next class. □

1.7. January 26th. Today we prove the previous lemma. Dorette wrote the proof down beforehand so I'm not going to live-Tex all of it, I'll just give sketches/hints. Before that, a correction from a couple classes back:

Consider the lifting problem:

$$\begin{array}{ccc} \{0, 1\} & \longrightarrow & X \\ \downarrow & \nearrow \text{dashed} & \downarrow \\ \{*\} & \longrightarrow & Y \end{array}$$

The square can only commute if the top horizontal arrow agrees on the fiber of g above the point picked out by the bottom arrow. A lift such as the dashed line above then exists whenever g only has empty or singleton fibers above each point. In this case weak orthogonality implies orthogonality.

(Sketch) of last Proposition. The third and fourth statements are duals so we only deal with the third. We show a chain of implications in the order they're stated skipped the fourth by duality.

For (1) implies (2) we only need to show maximality of either \mathcal{E} or \mathcal{M} . We have one of the containments in the assumption so show the other one. For this you pick $g \in \mathcal{E}$ or \mathcal{M} , factor it, and find a lift to show one of the maps is a section/retraction (depending on which one you started proving). Use that unique lift to find a lift for another square with both sides of it given by the same factorization of g . This gives a way to write g factoring through an iso and shows g satisfies the required maximality property

For (2) \implies (3), 'closed under composition' and 'containing all iso's' was proved in a previous class so we only need to show that the factorization is maximal. Play two factorizations against each other to set up a lifting problem with a unique solution. We ran into some issues with this proof so we're leaving it as an exercise.

For (3) \implies (5), suppose you have \mathcal{E} and define \mathcal{M} to be all the maps whose maximal factorization, $f = f' \circ e$ has e being an isomorphism. Check all the axioms for a factorization system are defined using the maximality property of the factorization \mathcal{E} -factorizations.

For (5) \implies (1), suppose you have a factorization system. We only need to show \mathcal{E} is left orthogonal to \mathcal{M} . Set up the lifting problem, factor the horizontal arrows and use closure under composition of \mathcal{E} and \mathcal{M} along with uniqueness of factorizations to solve the lifting problem uniquely. □

1.8. Jan 29. Snow day and Dorette was sick so no class.

1.9. **Jan 31st.** One last thing about factorization systems:

Lemma 28. *If $(\mathcal{E}, \mathcal{M})$ is a factorization system for \mathcal{C} then*

- (1) *If $g \circ f \in \mathcal{M}$ and $g \in \mathcal{M}$ then $f \in \mathcal{M}$*
- (2) *If $g \circ f \in \mathcal{M}$ and $f \in \mathcal{E}$ then $g \in \mathcal{E}$*
- (3) *\mathcal{M} contains all sections iff all \mathcal{E} maps that are sections are iso's.*
- (4) *\mathcal{E} contains all retractions iff all \mathcal{M} maps that are retractions are iso's.*

Solution. □

Examples. Isomorphisms with all the other arrows in any category (in either order) forms a factorization system. Epimorphisms and monomorphisms in **Set**, **Grp**, **Top**, form factorization systems and in the category of rings localizations and conservative morphisms form another important one in algebraic geometry.

Definition 29. A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ assigns objects to objects and arrows to arrows

$$F_0 : \mathcal{C}_0 \rightarrow \mathcal{D}_0, \quad F_1 : \mathcal{C}_1 \rightarrow \mathcal{D}_1$$

such that domains, codomains, identities, and composition are all preserved.

Examples. We can pick out objects, arrows, isomorphisms, in a category by looking at functors into out from \mathbb{K}, \neq , and the ‘walking isomorphism’ category (with 2 objects and 2 non-identity arrows that mutually inverse).

1.10. **Feb 7.**