ICS141: Discrete Mathematics for Computer Science I

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Originals by Dr. M. P. Frank and Dr. J.L. Gross
Provided by McGraw-Hill

Lecture 10

Chapter 2. Basic Structures

2.3 Functions

2.3 Functions

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- From calculus, you are familiar with the concept of a real-valued function f, which assigns to each number $x \in \mathbf{R}$ a value $y = f(x)$, where $y \in \mathbf{R}$.

- But, the notion of a function can also be naturally generalized to the concept of assigning elements of *any* set to elements of *any* set. (Also known as a *map*.)

Function: Formal Definition

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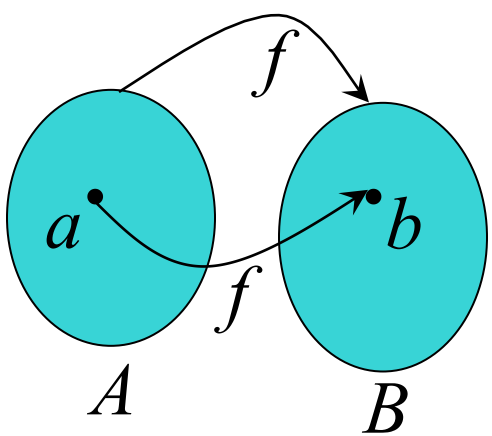
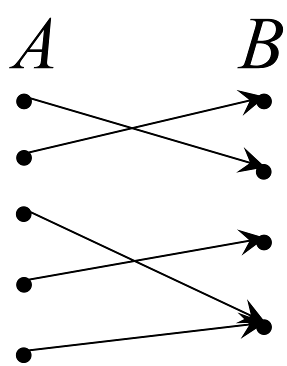
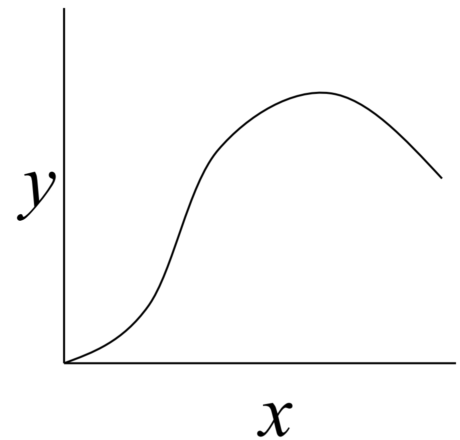
- For any sets *A* and *B*, we say that a ***function*** **(*or "mapping"*) *f from A to B* (*f* : *A* → *B*)** is a particular assignment of **exactly one element** $f(x) \in B$ to **each element** $x \in A$.
- Functions can be represented graphically in several ways:



Like Venn diagrams



Bipartite Graph



Plot

Some Function Terminology

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- If it is written that $f : A \rightarrow B$, and $f(a) = b$ (where $a \in A$ and $b \in B$), then we say:
  - A is the ***domain*** of f
  - B is the ***codomain*** of f
  - b is the ***image*** of a under f
    - a can not have more than 1 image
  - a is a ***pre-image*** of b under f
    - b may have more than 1 pre-image
  - The ***range*** $R \subseteq B$ of f is $R = \{b \mid \exists a\ f(a) = b\}$

Range versus Codomain

- The range of a function might *not* be its whole codomain.
- The codomain is the set that the function is *declared* to map all domain values into.
- The range is the *particular* set of values in the codomain that the function *actually* maps elements of the domain to.

Range vs. Codomain: Example

- Suppose I declare that: "*f* is a function mapping students in this class to the set of grades {A, B, C, D, F}."
- At this point, you know *f* 's codomain is: {A, B, C, D, F}, and its range is unknown!
- Suppose the grades turn out all As and Bs.
- Then the range of *f* is {A, B}, but its codomain is still {A, B, C, D, F}!

Function Operators

- +, × ("plus","times") are binary operators over **R**. (Normal addition & multiplication.)
- Therefore, we can also add and multiply two *real-valued functions* f,g: $\mathbf{R} \rightarrow \mathbf{R}$:
  - $(f + g)$: $\mathbf{R} \rightarrow \mathbf{R}$, where $(f + g)(x) = f(x) + g(x)$
  - (fg): $\mathbf{R} \rightarrow \mathbf{R}$, where $(fg)(x) = f(x)g(x)$
- <u>Example 6</u>:
  Let f and g be functions from **R** to **R** such that $f(x) = x^2$ and $g(x) = x - x^2$.
  What are the functions $f + g$ and fg?

Function Composition Operator

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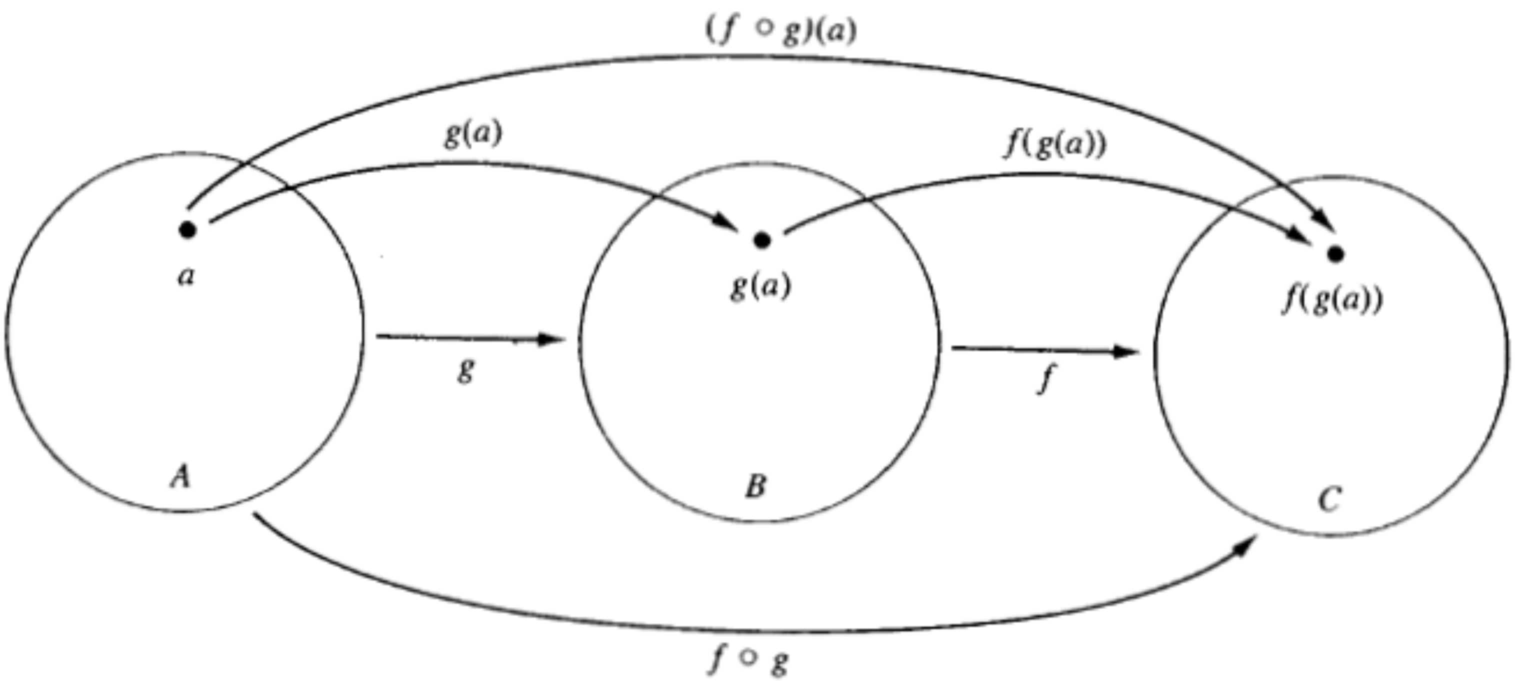
Note the match here. It's necessary!

- For functions $g: A \rightarrow B$ and $f: B \rightarrow C$, there is a special operator called ***compose*** ("$\circ$").
  - It <u>composes</u> (creates) a new function from f and g by applying f to the result of applying g.
  - We say $(f \circ g): A \rightarrow C$, where $(f \circ g)(a) = f(g(a))$.
  - Note: $f \circ g$ cannot be defined unless range of g is a subset of the domain of f.
  - Note $g(a) \in B$, so $f(g(a))$ is defined and $\in C$.
  - Note that $\circ$ is non-commuting. (Like Cartesian $\times$, but unlike $+$, $\wedge$, $\cup$) (Generally, $f \circ g \neq g \circ f$.)

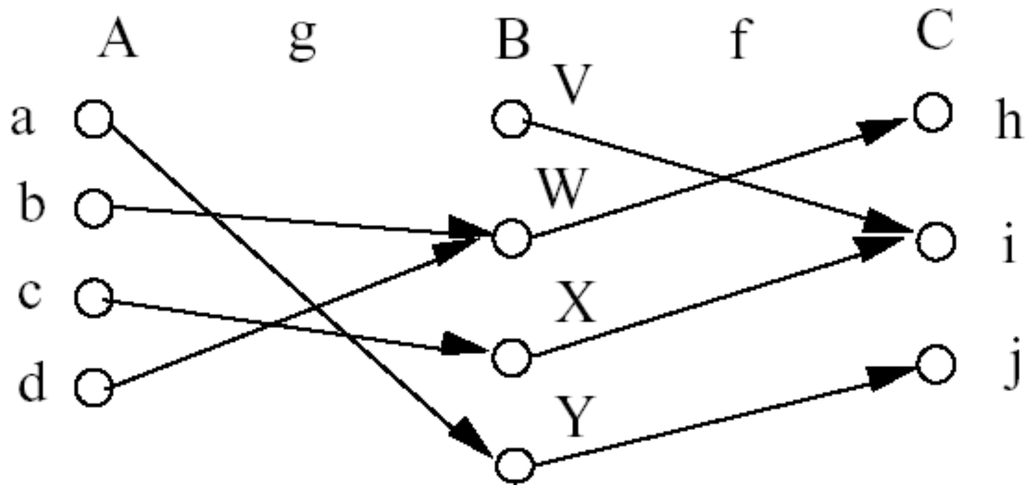
Function Composition Illustration

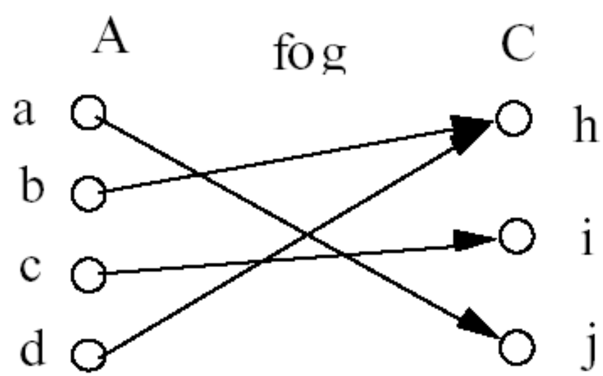
- $g: A \rightarrow B,\ f : B \rightarrow C$



Function Composition: Example

- $g: A \rightarrow B,\ \ f: B \rightarrow C$





Function Composition: Example

- Example 20: Let $g: \{a, b, c\} \to \{a, b, c\}$ such that

  $$g(a) = b,\ g(b) = c,\ g(c) = a.$$

  Let $f : \{a, b, c\} \to \{1, 2, 3\}$ such that

  $$f(a) = 3,\ f(b) = 2,\ f(c) = 1.$$

  What is the composition of f and g, and what is the composition of g and f ?

  - $f \circ g: \{a, b, c\} \to \{1, 2, 3\}$ such that

    $$(f \circ g)(a) = 2,\ (f \circ g)(b) = 1,\ (f \circ g)(c) = 3.$$

  - $g \circ f$ is not defined (why?)

Function Composition: Example

- If $f(x) = x^2$ and $g(x) = 2x + 1$, then what is the composition of f and g, and what is the composition of g and f ?
  - $(f \circ g)(x) = f(g(x))$
    $= f(2x+1)$
    $= (2x+1)^2$
  - $(g \circ f)(x) = g(f(x))$
    $= g(x^2)$
    $= 2x^2 + 1$

Note that $f \circ g \neq g \circ f$. $(4x^2+4x+1 \neq 2x^2+1)$

Images of Sets under Functions

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- Given $f : A \rightarrow B$, and $S \subseteq A$,
- The ***image*** of S under f is simply the set of all images (under f) of the elements of S.

$$f(S) = \{f(t) \mid t \in S\}$$
$$= \{b \mid \exists t \in S: f(t) = b\}.$$

- Note the range of f can be defined as simply the image (under f) of f's domain.

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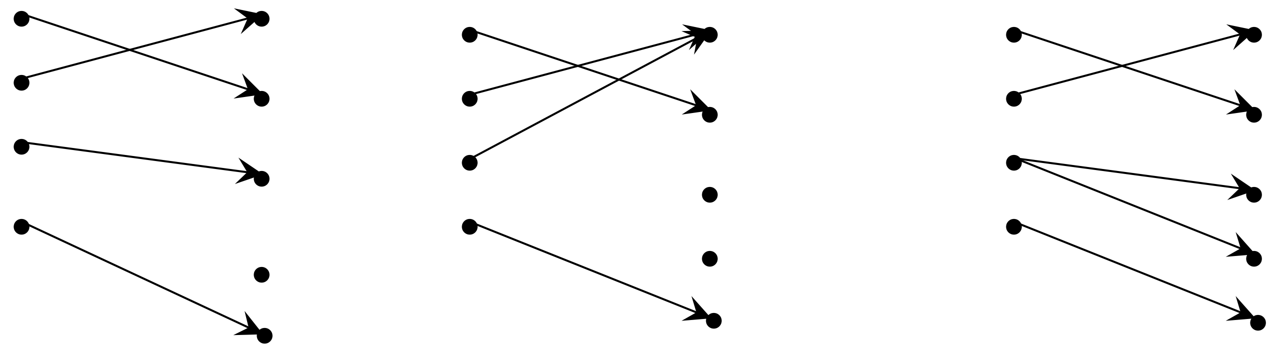
One-to-One Functions

- A function f is ***one-to-one*** (*1–1*), or ***injective***, or an ***injection***, iff $f(a) = f(b)$ implies that $a = b$ for all a and b in the domain of f (i.e. every element of its range has *only* 1 pre-image).
  - Formally, given $f : A \rightarrow B$,
    "f is injective": $\forall a,b\ (f(a) = f(b) \rightarrow a = b)$ or equivalently $\forall a,b\ (a \neq b \rightarrow f(a) \neq f(b))$
- Only <u>one</u> element of the domain is mapped <u>to</u> any given <u>one</u> element of the range.
  - Domain & range have the same cardinality. What about codomain?

One-to-One Illustration

- Bipartite (2-part) graph representations of functions that are (or not) one-to-one:



One-to-one Not one-to-one Not even a function!

- Example 8:
  Is the function $f : \{a, b, c, d\} \rightarrow \{1, 2, 3, 4, 5\}$ with $f(a) = 4$, $f(b) = 5$, $f(c) = 1$, and $f(d) = 3$ one-to-one?
- Example 9:
  Let $f : \mathbf{Z} \rightarrow \mathbf{Z}$ such that $f(x) = x^2$. Is f one-to-one?

Sufficient Conditions for 1–1ness

- For functions f over numbers, we say:
  - f is ***strictly*** (or ***monotonically***) ***increasing*** iff $x > y \rightarrow f(x) > f(y)$ for all x, y in domain;
  - f is ***strictly*** (or ***monotonically***) ***decreasing*** iff $x > y \rightarrow f(x) < f(y)$ for all x, y in domain;

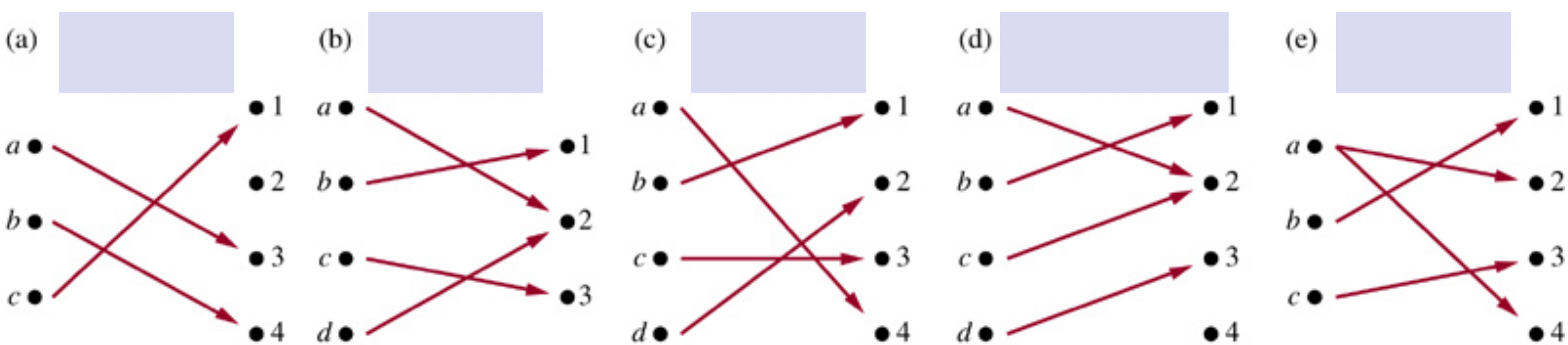
- If f is either strictly increasing or strictly decreasing, then f is one-to-one.
  - *E.g.* x^3

Onto (Surjective) Functions

- A function $f : A \rightarrow B$ is ***onto*** or ***surjective*** or a ***surjection*** iff for every element $b \in B$ there is an element $a \in A$ with $f(a) = b$ ($\forall b \in B, \exists a \in A: f(a) = b$) (i.e. its range is equal to its codomain).
- Think: An *onto* function maps the set *A* onto (over, covering) the *entirety* of the set *B*, not just over a piece of it.
- *E.g.*, for domain & codomain **R**, x^3 is onto, whereas x^2 isn't. (Why not?)

Illustration of Onto

- Some functions that are, or are not, *onto* their codomains:



- <u>Example13</u>: Is the function $f(x) = x + 1$ from the set of integers to the set of integers onto?

Bijections and Inverse Function

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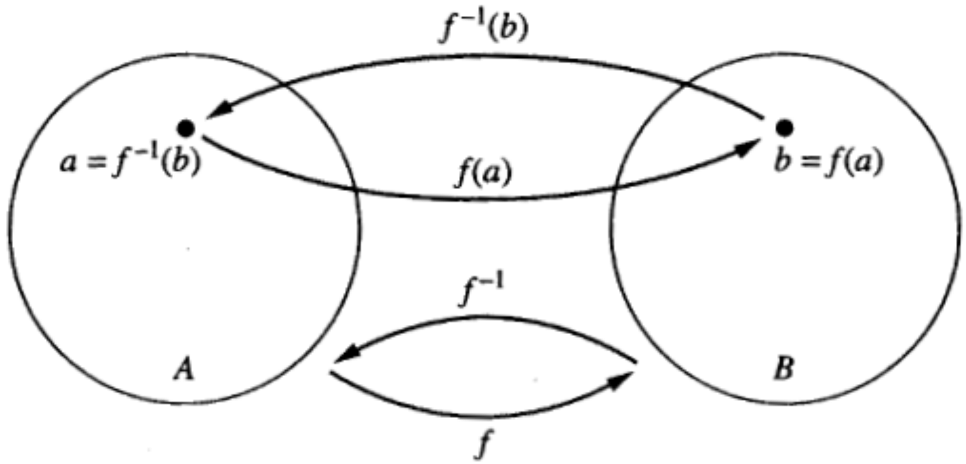
- A function *f* is said to be *a* ***one-to-one correspondence***, or *a* ***bijection***, or *reversible*, or *invertible*, iff it is both one-to-one and onto.

- Let $f : A \to B$ be a bijection.
  The ***inverse function*** of *f* is the function that assigns to an element $b \in B$ the unique element $a \in A$ such that $f(a) = b$.
  The inverse function of *f* is denoted by $f^{-1}: B \to A$.
  Hence, $f^{-1}(b) = a$ when $f(a) = b$.

Inverse Function Illustration

- Let $f: A \to B$ be a bijection



- Example 16: Let $f : \{a, b, c\} \to \{1, 2, 3\}$ such that $f(a) = 2$, $f(b) = 3$, $f(c) = 1$. Is f invertible, and if it is, what is its inverse? Yes. $f^{-1}(1) = c$, $f^{-1}(2) = a$, $f^{-1}(3) = b$
- Example 18: Let f be the function from **R** to **R** with $f(x) = x^2$. Is f invertible? No. f is not a one-to-one function. So it's not invertible.

Mappings in Java

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- A discrete function can be represented by a `Map` interface or `HashMap` class in Java programming language
  - ```
    Map map<Integer,String>
          = new HashMap<Integer,String>();
    ```
  - Here, the domain is `Integer`, the codomain is `String`
- We can construct such a mapping by putting all pairs {a, f(a)} into our `map`. (a is the *key*, f(a) is the *value*.)
  - `map.put(2,"Jan");`
  - `for (Kid kid:kids) {map.put(kid.id,kid.name);}`
- If we put another pair with the same key, it will overwrite the previous pair – it's not a function! (May be a bug…)
    ```

Image, Range, Bijection in Java

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- `Map.keys()` returns the **image**
  - it's a Java `Set`!
- `map.values()` returns the **range**
  - it's a Java `Set`!
- Is a `map` a bijection?
  Iff the cardinalities of the **image** and **range** are the same:
  - ```
    if (map.keys().size()==map.values().size()) {
      System.out.println("map is a bijection");
    }
    ```
    ```

Inverse Function in Java

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- Let's construct an inverse!
- Prepare the inverse function:
  - ```
    Map inverse<String,Integer>
          = new HashMap<String,Integer>();
    ```
  - Here, the domain is `String`, the codomain is `Integer`
- Go through all keys in `map` (all elements of the **image**) and put each pair {value,key} into `inverse`:
  - ```
    for (Integer id:map.keys()) {
      String name = map.get(id);
      inverse.put(id:name,id);
    }
    ```