Section 2

Encoding of Data Types into $\mathbb{N}$

There are lots of different data types available.

Some data types have finite size.

  E.g. the type of Booleans $\{\text{true, false}\}$.

Some data types have infinite size but are still “small”.

  E.g. the type of natural numbers $\mathbb{N} = \{0, 1, 2, \ldots\}$. 
Some data types are “big”.

E.g. the set of subsets $\mathcal{P}(\mathbb{N})$ of $\mathbb{N}$.

Subsets of $\mathbb{N}$ have in general no finite description.

- Some are finite (e.g. $\{0, 1, 3\}$).
- Some can be described by formulae
  - E.g. the set of even numbers is
    \[
    \{ n \in \mathbb{N} \mid \exists m \in \mathbb{N}. n = 2m \}.
    \]

But there are subsets which cannot be described by formulae.

There is no way of associating a finite description to all elements of $\mathcal{P}(\mathbb{N})$.

- This will be shown in this section.
Size and Computability

- We can introduce a notion of computability for finite and for small infinite data types.
  - E.g. it makes sense to compute certain functions mapping natural numbers to natural numbers.

- We cannot introduce in general a notion of computability for big data types.
  - We cannot even represent its elements on the computer.
There are notions of computability for certain “big data types” which make use of approximations of elements of such data types.

Topic of intensive research in Swansea esp. of Ulrich Berger, Jens Blanck, Monika Seisenberger, John Tucker.

One considers especially $\mathbb{R}$ and sets of functions (E.g. $\mathbb{N} \rightarrow \mathbb{N}$, $(\mathbb{N} \rightarrow \mathbb{N}) \rightarrow \mathbb{N}$).

Not part of this lecture.
In this Section we will make precise the notion of size of a set.

- Notion of “cardinality” and “equinumerous”.
- We will introduce a hierarchy of sizes.
  - We will be able to distinguish between sizes of different “big” sets.

Countable sets will be the sets, which were called “small” above.

- This notion will include the finite sets.
Notions of Computability

- We will later introduce computability on $\mathbb{N}$.
- Computability on countable sets will in this section be reduced to computability on $\mathbb{N}$.
Structure of this Section

(a) Mathematical background.
(b) Cardinality.
(c) Countable sets.
(d) Reducing computability to $\mathbb{N}$.
(e) Encoding of some data types into $\mathbb{N}$.
(f) Further mathematical background: Partial functions.
(a) Mathematical Background

Some Standard Sets

\( \mathbb{N} \) is the set of natural numbers:

\[
\mathbb{N} := \{0, 1, 2, \ldots\}.
\]

Note that 0 is a natural number.

When counting, we start with 0:

- The element no. 0 of a sequence is what is usually called the first element:
  - E.g., in \( x_0, \ldots, x_{n-1}, x_0 \) is the first variable.
- The element no. 1 of a sequence is what is usually called the second element:
  - E.g., in \( x_0, \ldots, x_{n-1}, x_1 \) is the second variable.
- etc.
Some Standard Sets

\[ \mathbb{Z} \text{ is the set of integers:} \]

\[ \mathbb{Z} := \mathbb{N} \cup \{-n \mid n \in \mathbb{N}\} . \]

So

\[ \mathbb{Z} = \{\ldots, -4, -3, -2, -1, 0, 1, 2, 3, 4, \ldots, \} \]
Some Standard Sets

- $\mathbb{Q}$ is the set of rationals, i.e.

$$\mathbb{Q} := \left\{ \frac{x}{y} \mid x \in \mathbb{Z}, y \in \mathbb{N}, y \neq 0 \right\} .$$

- So $\mathbb{Q}$ contains $\frac{2}{17}$, $\frac{-3}{5}$, $\frac{-2}{3}$, etc.
- As usual we identify equal fractions e.g.

$$\frac{2}{4} = \frac{1}{2}.$$

- We write $-\frac{n}{m}$ instead of $\frac{-n}{m}$, e.g. $-\frac{1}{2} = \frac{-1}{2}$.
- As usual $\frac{z}{-m} := -\frac{z}{m}$, e.g. $\frac{1}{-2} := -\frac{1}{2}$.
Some Standard Sets

\( \mathbb{R} \) is the set of real numbers.

E.g.

- \( 0.333333 \cdots \in \mathbb{R} \),
- \( \sqrt{2} \in \mathbb{R} \),
- \( -\sqrt{2} \in \mathbb{R} \),
- \( \pi \in \mathbb{R} \).
Some Standard Sets

Assume $A$, $B$ are sets.

- $A \times B$ is the **product of $A$ and $B$**:

  $$A \times B := \{(x, y) \mid x \in A \land y \in B\}$$

- $A \rightarrow B$ is the set of functions $f : A \rightarrow B$. 
Assume $A$ is a set, $k \in \mathbb{N}$. Then $A^k$ is the set of $k$-tuples of elements of $A$ or $k$-fold Cartesian product of $A$ defined as follows:

$$A^k := \{(x_0, \ldots, x_{k-1}) \mid x_0, \ldots, x_{k-1} \in A\}.$$ 

Note that

$$A^0 = \{()\}$$

We identify $A^1$ with $A$. So we don’t distinguish between $(x)$ and $x$. 

### Some Standard Sets

CS_226 Computability Theory, Lent Term 2007, Sec. 2 (a)
We define

\[ A^* := \{ (a_0, \ldots, a_{k-1}) \mid k \in \mathbb{N}, a_0, \ldots, a_{k-1} \in A \} \]

So \( A^* \) is

- the set of sequences of elements of \( A \) (of arbitrary length),
- also called the set of lists of \( A \),
- or \( A \)-Kleene-Star.

So \( A^* \) is the union of all \( A^k \) for \( k \in \mathbb{N} \), i.e.

\[ A^* = \bigcup_{k \in \mathbb{N}} A^k \]
Remark:

- $A^*$ can be considered as the set of strings having letters in the alphabet $A$.
- E.g. if
  
  $$ A = \{ a, b, c, \ldots, z \} $$
  
  then $A^*$ is the set of strings formed from lower case letters.
- So $(r, e, d)$ stands for the string “red”.
- $A^k$ is the set of strings of length $k$ from alphabet $A$. 
$\mathcal{P}(X)$

- $\mathcal{P}(X)$, the powerset of $X$, is the set of all subsets of $X$.
- For finite sets $X$, the power set of $X$ will be finite:

$$\mathcal{P} \left( \{0, 1, 2\} \right) = \{\emptyset\},$$
$$\{0\}, \{1\}, \{2\},$$
$$\{0, 1\}, \{0, 2\}, \{1, 2\},$$
$$\{0, 1, 2\}\}$$

- For infinite sets $X$ we will see that the $X$ is big ("uncountable").
- Therefore we cannot write down the elements of $\mathcal{P}(X)$ for such $X$. 

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**Definition 2.1**

Let $f : A \rightarrow B$, $A' \subseteq A$.

(a) $f[A'] := \{ f(a) \mid a \in A' \}$ is called the **image of $A'$ under $f$**.

(b) The image of $A$ under $f$ (i.e. $f[A]$) is called the **image of $f$**.
Image of $f$

![Diagram showing the image of $f$]

- $A$: elements $a$, $b$, $c$, $d$
- $B$: elements $e$, $f$, $g$, $h$
- $f$: mappings from $A$ to $B$
Image of $f$

Image of $A'$ under $f$. 
Image of $f$

Image of $A'$ under $f$.

$f[A'] = \{e, f\}$
Image of $f$

Image of $f$.

$f[A] = \{e, f, g\}$
Injective/Surjective/Bijective

**Definition 2.2**

*Let* $A$, $B$ *be sets,* $f : A \to B$.

(a) $f$ *is injective* *or an injection* or *one-to-one*, if

$f$ applied to different elements of $A$ has different results:

$\forall a, b \in A. a \neq b \rightarrow f(a) \neq f(b)$.

(b) $f$ *is surjective* *or a surjection* or *onto*, if

every element of $B$ is in the image of $f$:

$\forall b \in B. \exists a \in A. f(a) = b$.

(c) $f$ *is bijective* *or a bijection* or a *one-to-one correspondence*

if it is both surjective and injective.
Visualisation of “Injective”

If we visualise a function by having arrows from elements $a \in A$ to $f(a) \in B$ then we have the following:

- A function is **injective**, if for every element of $B$ there is at most one arrow pointing to it:
A function is **surjective**, if for every element of $B$ there is at least one arrow pointing to it:
A function is **bijective**, if for every element of \( B \) there is exactly one arrow pointing to it:

Note that, since we have a function, for every element of \( A \) there is exactly one arrow originating from there.
Remark

The injective, surjective, bijective functions are closed under composition:

If \( f : A \to B \) and \( g : B \to C \) are injective (or surjective or bijective), then \( g \circ f : A \to C \) is injective (surjective, bijective, respectively) as well.

Proof: See mathematics lectures or easy exercise.
Infinite Sequences

- An infinite sequence of elements of a set $B$ is an enumeration of certain elements of $B$ by natural numbers.
- E.g. the sequence of even numbers is $(0, 2, 4, 6, 8, \ldots)$
- We might repeat elements, e.g.
  
  $(0, 2, 0, 2, 0, 2, \ldots)$
Infinite Sequences

Sequences of natural numbers are written as

$$ (a_n)_{n \in \mathbb{N}} $$

which stands for

$$ (a_0, a_1, a_2, \ldots) $$

So the sequence of even numbers is $ (a_n)_{n \in \mathbb{N}} $ where

$$ a_n = 2n $$
A sequence \((a_n)_{n \in \mathbb{N}}\) of elements in \(A\) is nothing but a function \(f : \mathbb{N} \rightarrow A\), s.t. \(f(n) = a_n\).

In fact we will identify functions \(f : \mathbb{N} \rightarrow A\) with infinite sequences of elements of \(A\).
So the following denotes the same mathematical object:

- The function \( f : \mathbb{N} \rightarrow \mathbb{N}, f(n) = \begin{cases} 0 & \text{if } n \text{ is odd,} \\ 1 & \text{if } n \text{ is even.} \end{cases} \)

- The sequence \((1, 0, 1, 0, 1, 0, \ldots)\).

- The sequence \((a_n)_{n \in \mathbb{N}}\) where \(a_n = \begin{cases} 0 & \text{if } n \text{ is odd,} \\ 1 & \text{if } n \text{ is even.} \end{cases} \)
Infinite Sequences

- Occasionally, we will enumerate sequences by different index sets.
  
  - E.g. we consider a sequence indexed by non-zero natural numbers
    \[(a_n)_{n \in \mathbb{N} \setminus \{0\}}\]
  
  or a sequence indexed by integers
    \[(a_z)_{z \in \mathbb{Z}}\]

- A sequence \((a_x)_{x \in B}\) of elements in \(A\) is nothing but the function
  \[f : B \rightarrow A, \quad f(x) = a_x\]
\(\lambda\)-Notation

\(\lambda x.t\) means in an informal setting the function mapping \(x\) to \(t\).

E.g.

- \(\lambda x.x + 3\) is the function \(f\) s.t. \(f(x) = x + 3\).
- \(\lambda x.\sqrt{x}\) is the function \(f\) s.t. \(f(x) = \sqrt{x}\).

This notation used, if one one wants to introduce a function without giving it a name.

Domain and codomain not specified – when this notation is used, this will be clear from the context.
The “dot”-notation.

In expressions like

$$\forall x. A(x) \land B(x)$$

the quantifier ($$\forall x.$$) is as far as possible:

In

$$\forall x. A(x) \land B(x)$$

$$\forall x.$$ refers to

$$A(x) \land B(x)$$
The “dot”-notation.

In

\((A \rightarrow \forall x. B(x) \land C(x)) \lor D(x)\)

\(\forall x\) refers only to

\(B(x) \land C(x)\)

This is the maximum scope possible. It doesn’t make sense to include “\(\lor D(x)\)” into the scope.
The “dot”-notation.

\[ \exists x. A(x) \land B(x) \]

\[ \exists x \text{ refers to} \]

\[ A(x) \land B(x) \]

\[ (A \land \exists x. B(x) \lor C(x)) \land D(x) \]

\[ \exists x \text{ refers to} \]

\[ B(x) \lor C(x) \]
The “dot”-notation.

This applies as well to $\lambda$-expressions.

So

$$\lambda x. x + x$$

is the function taking an $x$ and returning $x + x$. 
A **predicate** on a set $A$ is a property $P$ of elements of $A$. In this lecture, $A$ will usually be $\mathbb{N}^k$ for some $k \in \mathbb{N}$, $k > 0$.

We write $P(a)$ for “predicate $P$ is true for the element $a$ of $A$”.

We often write “$P(x)$ holds” for “$P(x)$ is true”.
We can use $P(a)$ in formulas. Therefore:

- $\neg P(a)$ (“not $P(a)$”) means that “$P(a)$ is not true”.

- $P(a) \land Q(b)$ means that “both $P(a)$ and $Q(b)$ are true”.

- $P(a) \lor Q(b)$ means that “$P(a)$ or $Q(b)$ is true”.

(We have inclusive or: if both $P(a)$ and $Q(b)$ are true, then $P(a) \lor Q(b)$ is true as well).

- $\forall x \in B. P(x)$ means that “for all elements $x$ of the set $B$ $P(x)$ is true”.

- $\exists x \in B. P(x)$ means that “there exists an element $x$ of the set $B$ s.t. $P(x)$ is true”.

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In this lecture, “relation” is another word for “predicate”.

We identify a predicate $P$ on a set $A$ with $\{x \in A \mid P(x)\}$. Therefore predicates and sets will be identified. E.g., if $P$ is a predicate,

- $x \in P$ stands for $x \in \{x \in A \mid P(x)\}$, which is equivalent to $P(x)$,
- $\forall x \in P. \varphi(x)$ for a formula $\varphi$ stands for $\forall x. P(x) \rightarrow \varphi(x)$.
- etc.
An \textit{n-ary relation} or predicate on \( \mathbb{N} \) is a relation \( P \subseteq \mathbb{N}^n \).

A \textit{unary}, \textit{binary}, \textit{ternary} relation on \( \mathbb{N} \) is a 1-ary, 2-ary, 3-ary relation on \( \mathbb{N} \), respectively.

An \textit{n-ary function} on \( \mathbb{N} \) is a function \( f : \mathbb{N}^n \to \mathbb{N} \).

A \textit{unary}, \textit{binary}, \textit{ternary} function on \( \mathbb{N} \) is a 1-ary, 2-ary, 3-ary function on \( \mathbb{N} \), respectively.
In many expressions we will have arguments, to which we don’t refer explicitly.

**Example:** Variables $x_0, \ldots, x_{n-1}$ in

$$f(x_0, \ldots, x_{n-1}, y) = \begin{cases} g(x_0, \ldots, x_{n-1}), & \text{if } y = 0, \\ h(x_0, \ldots, x_{n-1}), & \text{if } y > 0. \end{cases}$$

We abbreviate $x_0, \ldots, x_{n-1}$ by $\vec{x}$.

Then the above can be written shorter as

$$f(\vec{x}, y) = \begin{cases} g(\vec{x}), & \text{if } y = 0, \\ h(\vec{x}), & \text{if } y > 0. \end{cases}$$

In general, $\vec{x}$ stands for $x_0, \ldots, x_{n-1}$, where the number of arguments $n$ is clear from the context.
Examples

- If

\[ f : \mathbb{N}^{n+1} \rightarrow \mathbb{N} \]

then in \( f(\vec{x}, y) \),
\( \vec{x} \) needs to stand for \( n \) arguments.
Therefore

\[ \vec{x} = x_0, \ldots, x_{n-1} \]

- If

\[ f : \mathbb{N}^{n+2} \rightarrow \mathbb{N} \]

then in \( f(\vec{x}, y) \),
\( \vec{x} \) needs to stand for \( n + 1 \) arguments, so

\[ \vec{x} = x_0, \ldots, x_n \]
Examples

- If $P$ is an $n + 4$-ary relation, then in $P(\vec{x}, y, z)$, $\vec{x}$ stands for $x_0, \ldots, x_{n+1}$

- Similarly, we write $\vec{y}$ for $y_0, \ldots, y_{n-1}$

where $n$ is clear from the context.

- Similarly for $\vec{z}, \vec{n}, \vec{m}, \ldots$
Notation

$\forall \vec{x} \in \mathbb{N}. \varphi(\vec{x})$

stands for

$\forall x_0, \ldots, x_{n-1} \in \mathbb{N}. \varphi(x_0, \ldots, x_{n-1})$

where the number of variables $n$ is implicit (and usually unimportant).

$\exists \vec{x} \in \mathbb{N}. \varphi(\vec{x})$

is to be understood similarly.
Notation

\[ \{ \vec{x} \in \mathbb{N}^n \mid \varphi(\vec{x}) \} \]

is to be understood as

\[ \{(x_0, \ldots, x_{n-1}) \in \mathbb{N}^n \mid \varphi(x_0, \ldots, x_{n-1}) \} \]

\[ \{(\vec{x}, y, z) \in \mathbb{N}^n \mid \varphi(\vec{x}, y, z) \} \]

is to be understood as

\[ \{(x_1, \ldots, x_{n-3}, y, z) \in \mathbb{N}^n \mid \varphi(x_0, \ldots, x_{n-3}, y, z) \} \]

Similar notations are to be understood analogously.
(b) Cardinality

In this subsection, we will make precise the notion of “small”, “big” sets above.

So we need a notion of size of a set.

For finite sets one can introduce a number for the size of a set.

For infinite sets, introducing such numbers (cardinality) is beyond the scope of this lectures

However, we can introduce a notion of relative size, namely what it means for one set to be smaller/equal/greater in size than another set.

Equinumerous will mean “equal in size”.
Number of Elements

**Notation 2.3**

*If* $A$ *is a finite set, let* $|A|$ *be the number of elements in* $A$.

**Remark 2.4**

*One sometimes writes* $\#A$ *for* $|A|$.
Cardinality of Finite Sets

If $A$ and $B$ are finite sets, then $|A| = |B|$, if and only if there is a bijection between $A$ and $B$:

- **Bijection exists**:
  - $a$ maps to $d$
  - $b$ maps to $e$
  - $c$ maps to $f$

- **No Bijection**:
  - $a$ maps to $d$
  - $b$ maps to $e$
  - $c$ maps to some other element
Cardinality of Finite Sets

The above can be generalized to arbitrary (possibly infinite sets) as follows:
Cardinality of Sets

**Definition 2.5**

*Two sets $A$ and $B$ are equinumerous or “have the same cardinality”, in mathematical notation*

$$A \approx B$$

*if there exists a bijection*

$$f : A \rightarrow B$$

**Remark 2.6**

*If $A$ and $B$ are finite sets, then $A \approx B$ if and only $A$ and $B$ have the same number of elements, i.e. $|A| = |B|$. 
Change of Notation

Until the academic year 2004/05, we used in lectures
“have the same cardinality” instead of
“equinumerous”,
and $\simeq$ instead of $\approx$.
Note that $\simeq$ is used (and was used) for partial
equality as well.
Change of notation in order to avoid the
overloading of notation.
Please take this into account when looking at old
exams and other lecture material.
Both notions occur as well in the literature and might be
used in other modules.
In set theory there exists the notion of a **cardinality**, which is some kind of number (an **ordinal**) which measures the size of a set.

Then one can show:

\[ A \approx B \text{ iff the cardinality expressed as an ordinal for } A \text{ and } B \text{ is the same.} \]

However, this notion is beyond the scope of this module.
Lemma 2.7
\(\approx\) is an equivalence relation, i.e. for all sets \(A, B, C\) we have:

(a) **Reflexivity.** \(A \approx A\).

(b) **Symmetry.** If \(A \approx B\), then \(B \approx A\).

(c) **Transitivity.** If \(A \approx B\) and \(B \approx C\), then \(A \approx C\).

Proof:
(a): The function \(\text{id} : A \rightarrow A\), \(\text{id}(a) = a\) is a bijection.

(b): If \(f : A \rightarrow B\) is a bijection, so is its inverse \(f^{-1}\).

(c): If \(f : A \rightarrow B\) and \(g : B \rightarrow C\) are bijections, so is the composition \(g \circ f : A \rightarrow C\).
Meaning of the above

That $\approx$ is an equivalence relation means that it has properties we expect of a relation expressing that two sets have the same size:

- Every set has the same size as itself
  
  $$A \approx A$$

- If $A$ has the same size as $B$, then $B$ has the same size as $A$.
  
  $$A \approx B \rightarrow B \approx A$$

- If $A$ has the same size as $B$ and $B$ has the same size as $C$ then $A$ has the same size as $C$:
  
  $$(A \approx B \land B \approx C) \rightarrow A \approx C$$
Meaning of the above

- If we wrongly defined $A$ and $B$ to have the same size if there is an injection from $A$ to $B$ then symmetry wouldn’t hold.

- So there is something to be shown, the language notation we use only suggests that the above mentioned properties hold.
  
  - Don’t let yourself be deceived by language!
Cardinality of the Power Set

**Theorem 2.8**
A set $A$ and its power set $\mathcal{P}(A) := \{B \mid B \subseteq A\}$ are never equinumerous:

$$A \not\approx \mathcal{P}(A)$$
Stronger Result

- In fact we will show something even stronger: For any set $A$ the following holds: there is no surjection
  \[ C : A \rightarrow \mathcal{P}(A) \]

- If this is shown, then we know that there is no bijection $C : A \rightarrow \mathcal{P}(A), A \not\approx \mathcal{P}(A)$.

**Remark on Notation:**
- We write here the capital letter $C$ instead of the usual letters $f$, $g$ etc. for functions, in order to flag that $C(a)$ is a set.
- For notational convenience we write $C_a$ instead of $C(a)$, so $C_a$ is “the $a$th set enumerated by the function $C$”.
Proof

A typical diagonalisation argument.

First consider the case $A = \mathbb{N}$.

Assume $C : \mathbb{N} \to \mathcal{P}(\mathbb{N})$ is a surjection.

We define a set $D \subseteq \mathbb{N}$ s.t. $D \neq C_n$ for every $n \in \mathbb{N}$.

$D = C_n$ will be violated at element $n$:

- If $n \in C_n$, we add $n$ not to $D$, therefore $n \in C_n \land n \notin D$.
- If $n \notin C_n$, we add $n$ to $D$, therefore $n \notin C_n \land n \in D$.

On the next slide we take as an example some function $C : \mathbb{N} \to \mathcal{P}(\mathbb{N})$ and show how to construct a set $D$ s.t. $C_n \neq D$ for all $n \in \mathbb{N}$. 
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]

\[ D = \{ \} \]
Example

\[
C_0 = \{ 0, 1, 2, 3, 4, \ldots \}
\]

\[
C_1 = \{ 0, 2, 4, \ldots \}
\]

\[
D = \{ 2, 4, \ldots \}
\]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ D = \{ 1, \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 1, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 2, 3, \ldots \} \]

\[ D = \{ 1, \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 3, \ldots \} \]

\[ D = \{ 1, 2, \ldots \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 3, \ldots \} \]
\[ C_3 = \{ 0, 1, 3, 4, \ldots \} \]
\[ D = \{ 1, 2, \ldots \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 3, \ldots \} \]
\[ C_3 = \{ 0, 1, 3, 4, \ldots \} \]

\[ D = \{ 1, 2, \ldots \} \]
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 3, \ldots \} \]
\[ C_3 = \{ 0, 3, 4, \ldots \} \]
\[ D = \{ 1, 2, \ldots \} \]

We were going through the diagonal in the above matrix.
Example

\[ C_0 = \{ 0, 1, 2, 3, 4, \ldots \} \]
\[ C_1 = \{ 0, 2, 4, \ldots \} \]
\[ C_2 = \{ 1, 3, \ldots \} \]
\[ C_3 = \{ 0, 1, 3, 4, \ldots \} \]
\[ D = \{ 1, 2, \ldots \} \]

We were going through the diagonal in the above matrix. Therefore this proof is called a \textit{diagonalisation} argument.
Proof

So we define

\[ D := \{ n \in \mathbb{N} \mid n \not\in C_n \} . \]

We have \( D \neq C_n \) for all \( n \):

Assume \( D = C_n \).

- If \( n \in D \), then by the definition of \( D \) we have \( n \not\in C_n \), therefore by \( D = C_n \) we get \( n \not\in D \), a contradiction.

- If \( n \not\in D \), then by the definition of \( D \) we have \( n \in C_n \), therefore by \( D = C_n \) we get \( n \in D \), a contradiction.

Therefore we obtain a contradiction in both cases, \( D \neq C_n \).

Therefore \( D \) is not in the image of \( C \), so \( C \) is not a surjection, a contradiction.
In short, the above argument for \( A = \mathbb{N} \) reads as follows:

Assume \( C : \mathbb{N} \to \mathcal{P}(\mathbb{N}) \) is a surjection.
Define
\[
D := \{ n \in \mathbb{N} \mid n \notin C_n \}.
\]

Since \( C \) is surjective, \( D \) must be in the image of \( C \).
Assume \( D = C_n \).
Then we have
\[
\begin{align*}
 n \in D \quad & \iff \quad n \notin C_n \\
 D = C_n \quad & \iff \quad n \notin D \\
 & \quad \text{a contradiction}
\end{align*}
\]
General Situation

For general $A$, the proof is almost identical:
Assume $C : A \rightarrow \mathcal{P}(A)$ is a surjection.
We define a set $D$, s.t. $D = C_a$ is violated for $a$:

$$D := \{ a \in A \mid a \notin C_a \}$$

Since $C$ is surjective, $D$ must be in the image of $C$.
Assume $D = C_a$. Then we have

$$a \in D \iff D = C_a \iff a \notin C_a$$
Definition of $D$ \quad $a \notin D$ \quad a contradiction
\[ \mathcal{P}(A) \text{ and } A \rightarrow \{0, 1\} \]

**Lemma 2.9** For every set \( A \)

\[ \mathcal{P}(A) \cong (A \rightarrow \{0, 1\}) \]
Proof

Let for $B \in \mathcal{P}(A)$

$$
\chi_B : A \rightarrow \{0, 1\}
$$

$$
\chi_B(x) := \begin{cases} 
1 & \text{if } x \in B, \\
0 & \text{if } x \notin B.
\end{cases}
$$

$\chi_B$ is called the **characteristic function of $B$**.

If we consider 0 as false and 1 as true, then

- $\chi_B(x)$ is true, if $x \in B$, and
- $\chi_B(x)$ is false, if $x \notin B$,

Therefore $\chi_B$ is the function, which determines whether its argument is in $B$ or not.
**Example:** $B = \text{set of Odd Numbers}$

\[
\chi_B(n) = \begin{cases} 
0 & \text{if } n \text{ is even,} \\
1 & \text{if } n \text{ is odd.}
\end{cases}
\]
Proof

- $\chi$ is a function from $\mathcal{P}(\mathbb{N})$ to $\mathbb{N} \rightarrow \{0, 1\}$, where we write the application of $\chi$ to an element $B$ as $\chi_B$ instead of $\chi(B)$.

- We show that $\chi$ is a bijection.
  - Then it follows that $\mathcal{P}(A) \approx (A \rightarrow \{0, 1\})$.

Jump over rest of proof
\[ \chi_B(x) := \begin{cases} 
1 & \text{if } x \in B, \\
0 & \text{if } x \notin B. 
\end{cases} \]

\( \chi \) has an inverse:

Define

\[ \chi^{-1} : (A \to \{0, 1\}) \to \mathcal{P}(A) \]

\[ \chi^{-1}(f) := \{ x \in A \mid f(x) = 1 \} \]
\(\chi\) and \(\chi^{-1}\) are inverse

\[
\chi_B(x) := \begin{cases} 
1 & x \in B, \\
0 & \text{otherwise}.
\end{cases}
\]

\[
\chi^{-1}(f) := \{ x \in A | f(x) = 1 \}
\]

- We show that \(\chi\) and \(\chi^{-1}\) are inverse:
- \(\chi^{-1} \circ \chi\) is the identity:
- If \(B \subseteq A\), then

\[
\chi^{-1}(\chi_B) = \{ x \in A | \chi_B(x) = 1 \}
= \{ x \in A | x \in B \}
= B
\]
\( \chi \) and \( \chi^{-1} \) are inverse

\[
\chi_B(x) := \begin{cases} 
1 & x \in B, \\
0 & \text{otherwise.}
\end{cases}
\]

\[
\chi^{-1}(f) := \{ x \in A \mid f(x) = 1 \}
\]

- \( \chi \circ \chi^{-1} \) is the identity:
- If \( f : A \to \{0, 1\} \), then

\[
\chi_{\chi^{-1}(f)}(x) = 1 \iff x \in \chi^{-1}(f) \iff f(x) = 1
\]
\( \chi \) and \( \chi^{-1} \) are inverse

\[
\chi_B(x) := \begin{cases} 
1 & x \in B, \\
0 & \text{otherwise.}
\end{cases}
\]

\[
\chi^{-1}(f) := \{ x \in A \mid f(x) = 1 \}
\]

and

\[
\chi_{\chi^{-1}(f)}(x) = 0 \iff x \notin \chi^{-1}(f) \iff f(x) \neq 1 \iff f(x) = 0 .
\]

Therefore \( \chi_{\chi^{-1}(f)} = f \).
\( \chi \) and \( \chi^{-1} \) are inverse

It follows that \( \chi \) is bijective and therefore

\[
\mathcal{P}(A) \cong (A \rightarrow \{0, 1\})
\]
(c) Countable Sets

Definition 2.10

A set $A$ is **countable**, if it is finite or $A \approx \mathbb{N}$.

A set, which is not countable, is called **uncountable**.

Intuitively

- uncountable sets are very big
- countable sets are finite or small infinite sets.
  - Countable sets have at most the size of the $\mathbb{N}$. 

Relationship to Cardinality

Intuitively (this can be made mathematically precise) the cardinalities of sets start with the finite cardinalities 0, 1, 2, ... corresponding to finite sets having 0, 1, 2, ... elements.

All these cardinalities are different (for finite sets $A, B$ we have $A \approx B$ iff $A$ and $B$ have the same number of elements).

Then the next cardinality is that of $\mathbb{N}$.

Then we have higher cardinalities like the cardinality of $\mathcal{P}(\mathbb{N})$ (or $\mathbb{R}$).
Relationship to Cardinality

Countable sets are the sets having cardinality less than or equal the cardinality of $\mathbb{N}$.

Which means they have cardinality of $\mathbb{N}$ or finite cardinality.
Examples of (Un)countable Sets

- \( \mathbb{N} \) is countable.
- \( \mathbb{Z} := \{ \ldots, -2, -1, 0, 1, 2, \ldots \} \) is countable.
  
  We can enumerate the elements of \( \mathbb{Z} \) in the following way:
  
  0, -1, +1, -2, +2, -3, +3, -4, +4, \ldots
  
  So we have the following map:
  
  0 \mapsto 0, \quad 1 \mapsto -1, \quad 2 \mapsto 1, \quad 3 \mapsto -2, \quad 4 \mapsto 2, \quad \text{etc.}
  
  This map can be described as follows:
  
  \[ g : \mathbb{N} \rightarrow \mathbb{Z}, \]
  
  \[ g(n) := \begin{cases} 
  \frac{n}{2} & \text{if } n \text{ is even}, \\
  -\frac{n+1}{2} & \text{if } n \text{ is odd}. 
  \end{cases} \]
  
  **Exercise:** Show that \( g \) is bijective.
Examples of (Un)countable Sets

- \( \mathcal{P}(\mathbb{N}) \) is uncountable.
- \( \mathcal{P}(\mathbb{N}) \) is not finite.
- \( \mathbb{N} \nless \mathcal{P}(\mathbb{N}) \).
- \( \mathcal{P}(\{1, \ldots, 10\}) \) is countable.
- Since it is finite.
Characterisation of Countable Sets

**Lemma 2.11**
A set $A$ is countable, if and only if there is an injective map $g : A \rightarrow \mathbb{N}$.

**Remark 2.12**
Intuitively, Lemma 2.11 expresses: $A$ is countable, if we can assign to every element $a \in A$ a unique code $f(a) \in \mathbb{N}$. It is not required that each element of $\mathbb{N}$ occurs as a code.
Proof of Lemma 2.11, “⇒”

“⇒”:
Assume $A$ is countable.
Show that there exists an injective function $f : A \rightarrow \mathbb{N}$.

- Case $A$ is finite:
  Let $A = \{a_0, \ldots, a_n\}$, where $a_i$ are different.
  We can define $f : A \rightarrow \mathbb{N}$, $a_i \mapsto i$.
  $f$ is injective.

- Case $A$ is infinite:
  $A$ is countable, so there is a bijection from $A$ into $\mathbb{N}$,
  which is therefore injective.
Proof of Lemma 2.11, “⇐”

“⇐”: Assume \( f : A \rightarrow \mathbb{N} \) is injective. Show \( A \) is countable.
If \( A \) is finite, we are done.
Assume \( A \) is infinite. Then \( f \) is for instance something like the following:

\[
\begin{align*}
A & \rightarrow \mathbb{N} \\
\times^a & \rightarrow \times^0 \\
\times^b & \rightarrow \times^1 \\
\times^c & \rightarrow \times^2 \\
\times^d & \rightarrow \times^3 \\
\times^e & \rightarrow \times^4 \\
\times^f & \rightarrow \times^5 \\
\times^g & \rightarrow \times^6 \\
\times^h & \rightarrow \times^7 \\
\times^i & \rightarrow \times^8 \\
\times^j & \rightarrow \times^9
\end{align*}
\]
Proof of Lemma 2.11, “⇐”

In order to obtain a bijection \( g : A \to \mathbb{N} \), we need to jump over the gaps in the image of \( f \):

The remaining (very interesting) proof will not be given in the lecture. **Jump over remaining proof.**
Proof of Lemma 2.11, “⇐”

\[ f(a) = 1, \text{ which is the element number 0 in the image of } f. \]
\[ g \text{ should instead map } a \text{ to 0.} \]
Proof of Lemma 2.11, “⇐”

\[ f(b) = 4, \text{ which is the element number 1 in the image of } f. \]
\[ g \text{ should instead map } b \text{ to } 1. \text{ Etc.} \]
Proof of Lemma 2.11, “⇐”

1 is element number 0 in the image of $f$, because the number of elements $f(a')$ below $f(a)$ is 0.
Proof of Lemma 2.11, “⇐”

4 is element number 1 in the image of \( f \), because the number of elements \( f(a') \) below \( f(b) \) is 1.
So in general we define $g : A \rightarrow \mathbb{N}$. 

$$g(a) := |\{a' \in A \mid f(a') < f(a)\}|$$
Proof of Lemma 2.11, “⇐”

\[ g(a) := |\{ a' \in A \mid f(a') < f(a) \}| \]

\( g \) is well defined, since \( f \) is injective, so the number of \( a' \in A \) s.t. \( f(a') < f(a) \) is finite.
Proof of Lemma 2.11, “⇐”

\[ g(a) = \left| \left\{ a' \in A \mid f(a') < f(a) \right\} \right| \]

We show that \( g \) is a bijection:

- **\( g \) is injective:**
  Assume \( a, b \in A, a \neq b. \)
  Show \( g(a) \neq g(b). \)
  By the injectivity of \( f \) we have \( f(a) \neq f(b). \)
  Let for instance \( f(a) < f(b). \)
Proof of Lemma 2.11, “⇐”
Proof of Lemma 2.11, “⇐”

Then

\[\{ a' \in A \mid f(a') < f(a) \} \subset \neq \{ a' \in A \mid f(a') < f(b) \},\]
Proof of Lemma 2.11, “⇐”

therefore

\[ g(a) = |\{a' \in A \mid f(a') < f(a)\}| < |\{a' \in A \mid f(a') < f(b)\}| = g(b) , \]
Proof of Lemma 2.11, "⇐"

therefore

\[ g(a) = |\{a' \in A \mid f(a') < f(a)\}| < |\{a' \in A \mid f(a') < f(b)\}| = g(b) , \]

\[ g(a) \neq g(b) . \]
Proof of Lemma 2.11, “⇐”

\[ g(a) = \left| \{ a' \in A \mid f(a') < f(a) \} \right| \]

\( g \) is surjective:
We define by induction on \( k \) for \( k \in \mathbb{N} \) an element \( a_k \in A \)
s.t. \( g(a_k) = k \). Then the assertion follows:
Assume we have defined already \( a_0, \ldots, a_{k-1} \).
Proof of Lemma 2.11, “⇐”

There exist infinitely many \( a' \in A \), \( f \) is injective, so there must be at least one \( a' \in A \) s.t. \( f(a') > f(a_{k-1}) \).
Proof of Lemma 2.11, “⇐”

There exists \( a' \in A \) s.t. \( f(a') > f(a_{k-1}) \).

Let \( n \) be minimal s.t. \( n = f(a) \) for some \( a \in A \) and \( n > f(a_{k-1}) \).
Proof of Lemma 2.11, “⇐”

\[ a \in \{a'_0, a'_1, \ldots, a'_{k-1} \} \cap A \]
\[ n \text{ minimal s.t. } n = f(a') \text{ for some } a' \in A, \ n > f(a_{k-1}) \]

Let \( a \) be the unique element of \( A \) s.t. \( f(a) = n \).
Proof of Lemma 2.11, "⇐"

\[ n \text{ minimal s.t. } n = f(a) \text{ for some } a \in A, \quad n > f(a_{k-1}) \]

\[ f(a) = n \]

\[ \{a'' \in A \mid f(a'') < f(a)\} = \{a'' \in A \mid f(a'') < f(a_{k-1})\} \cup \{a_{k-1}\} \]
Proof of Lemma 2.11, “⇐”

Therefore \( g(a) = \left| \{ a'' \in A \mid f(a'') < f(a) \} \right| \)

\[ = \left| \{ a'' \in A \mid f(a'') < f(a_{k-1}) \} \right| + 1 \]

\[ = g(a_{k-1}) + 1 = k - 1 + 1 = k \, . \]

Let \( a_k := a \).
Corollary 2.13

(a) If \( B \) is countable and \( g : A \rightarrow B \) injective, then \( A \) is countable.

(b) If \( A \) is uncountable and \( g : A \rightarrow B \) injective, then \( B \) is uncountable.

(c) If \( B \) is countable and \( A \subseteq B \), then \( A \) is countable.

Proof:

(a) If \( B \) is countable, there exists an injection \( f : B \rightarrow \mathbb{N} \). But then \( f \circ g : A \rightarrow \mathbb{N} \) is an injection as well, therefore \( A \) is countable.


(c): By (a). (What is \( g \)?; exercise).
Corollary 2.13

(d) If $A$ is uncountable and $A \subseteq B$, then $B$ is uncountable.

(e) If $A \approx B$, then $A$ is countable if and only if $B$ is countable.

Proof:

- (d): By (c). Why? (Exercise).
- (e): By (a). Why?
Intuitively we can say:

That there exists an injective function

\[ f : A \rightarrow B \]

means that the size of \( A \) is less than or equal to the size of \( B \).

That \( A \subseteq B \) means that there is an injection from \( A \) into \( B \).

So the size of \( A \) is less than or equal to the size of \( B \).
Lemma 2.14

Let $A$ be a non-empty set.

$A$ is countable, if and only if there is a surjection $h : \mathbb{N} \to A$.

**Remark:** This explains the notion “countable”: A non-empty set is countable if we can enumerate its elements (repetitions are allowed).

**2nd Remark:** The empty set $\emptyset$ is countable, but there exists no surjection $h : \mathbb{N} \to \emptyset$ – in fact there exists no function $h : \mathbb{N} \to \emptyset$ at all.

Jump over Proof.
Proof of Lemma 2.14

“⇒”: Assume $A$ is non-empty and countable. Show there exists a surjection $f : \mathbb{N} \to A$.

Case $A$ is finite.
Assume $A = \{a_0, \ldots, a_n\}$.
Define $f : \mathbb{N} \to A$,

$$f(k) := \begin{cases} a_k & \text{if } k \leq n \, , \\ a_0 & \text{otherwise} \, . \end{cases}$$

$f$ is clearly surjective.
Proof of Lemma 2.14

Case $A$ is infinite.
$A$ is countable, so there exists a bijection from $\mathbb{N}$ to $A$, which is therefore surjective.
Proof of Lemma 2.14

“⇐”:

- Assume $h : \mathbb{N} \to A$ is surjective.
- Show $A$ is countable.
- Define

  \[ g : A \to \mathbb{N}, \quad g(a) := \min\{n \mid h(n) = a\} \, . \]

  - $g(a)$ is well-defined, since $h$ is surjective:
    - There exists some $n$ s.t. $h(n) = a$, therefore the minimal such $n$ is well-defined.
Proof of Lemma 2.14

\[ g : A \rightarrow \mathbb{N} , \]
\[ g(a) := \min\{ n \mid h(n) = a \} \]

It follows that for \( a \in A \) we have

\[ h(g(a)) = a . \]

Therefore \( g \) is injective:

If \( g(a) = g(a') \) then

\[ a = h(g(a)) = h(g(a')) = a' . \]

Therefore \( g : A \rightarrow \mathbb{N} \) is an injection, and by Lemma 2.11, \( A \) is countable.
Corollary

Corollary 2.15

(a) If $A$ is countable and $g : A \to B$ surjective, then $B$ is countable.

(b) If $B$ is uncountable and $g : A \to B$ surjective, then $A$ is uncountable.
Proof of Corollary 2.15 (a)

To be shown: If \( A \) is countable, \( g : A \rightarrow B \) is surjective, then \( B \) is countable as well.

So assume \( A \) is countable, \( g : A \rightarrow B \) is surjective.

If \( A \) is empty, then \( B \) is empty as well and therefore countable.

(We need to treat \( A = \emptyset \) as a special case, since in that case there exists no surjection \( f : \mathbb{N} \rightarrow A \) as assumed in the next step, even so \( A \) is countable).
Proof of Corollary 2.15 (a)

Otherwise there exists a surjection

\[ f : \mathbb{N} \rightarrow A \]

But then

\[ g \circ f : \mathbb{N} \rightarrow B \]

is a surjection as well, therefore \( B \) is countable.
Proof of Corollary 2.15 (b)

Follows by (a). Why?
Surjection and Size

Intuitively we can say:

That there exists a surjective function

\[ f : A \rightarrow B \]

means that the size of \( A \) is greater than or equal to the size of \( B \).
Examples of Uncountable Sets

**Lemma 2.16**

The following sets are uncountable:

(a) $\mathcal{P}(\mathbb{N})$.

(b) $F := \{ f \mid f : \mathbb{N} \to \{0, 1\}\}$.

(c) $G := \{ f \mid f : \mathbb{N} \to \mathbb{N}\}$.

(d) The set of real numbers $\mathbb{R}$.

- **Proof of (a):** $\mathcal{P}(\mathbb{N})$ is not finite, and by Theorem 2.7 $\mathbb{N} \not\approx \mathcal{P}(\mathbb{N})$.

- **Proof of (b):** By Lemma 2.9 $\mathcal{P}(\mathbb{N}) \approx (\mathbb{N} \to \{0, 1\})$. $\mathcal{P}(\mathbb{N})$ is uncountable, therefore $\mathbb{N} \to \{0, 1\}$ as well.

- **Proof of (c):** $F \subseteq G$, $F$ is uncountable, so $G$ is uncountable.
Idea of Proof of Lemma 2.16 (d)

In order to show \( \mathbb{R} \) is uncountable, it suffices to show that the half open interval \([0, 1[\) (i.e. \( \{x \in \mathbb{R} \mid 0 \leq x < 1\} \)) is uncountable).

Elements of \([0, 1[\) are in binary representation of the form

\[
(0.a_0a_1a_2a_3 \cdots)_2
\]

where \( a_i \in \{0, 1\} \).

\((a_n)_{n \in \mathbb{N}}\) is a function \( \mathbb{N} \rightarrow \{0, 1\} \).

If the function mapping sequences \((a_n)_{n \in \mathbb{N}}: \mathbb{N} \rightarrow \{0, 1\}\) to \( \mathbb{R} \) were injective, then we could conclude from \( \mathbb{N} \rightarrow \{0, 1\} \) uncountable that \([0, 1[\) and therefore \( \mathbb{R} \) are uncountable.
Idea of Proof of Lemma 2.16 (d)

However this function is not injective since
\[ 0.a_0a_1a_2 \cdots a_n011111 \cdots \text{ and } 0.a_0a_1a_2 \cdots a_n100000 \cdots \] are the same number.

This is similar to decimal representation, where
\[ 0.a_0a_1a_2 \cdots a_n099999 \cdots \text{ and } 0.a_0a_1a_2 \cdots a_n100000 \cdots \] are the same.

This problem can be overcome with some effort.

The detailed proof will be omitted in the lecture. 
Jump over Proof.
Proof of Lemma 2.16 (d)

Show $\mathbb{R}$ is uncountable.

By (b),

$$ F = \{ f \mid f : \mathbb{N} \rightarrow \{0, 1\} \} $$

is uncountable.

A first idea is to define a function

$$ f_0 : F \rightarrow \mathbb{R} , $$

$$ f_0(g) = (0.g(0)g(1)g(2)\cdots)_2 $$

Here the right hand side is a number in binary format.

If $f_0$ were injective, then by $F$ uncountable we could conclude $\mathbb{R}$ is uncountable.
Proof of Lemma 2.16 (d)

Show \( \mathbb{R} \) is uncountable.

The problem is that

\[
(0.a_0a_1 \cdots a_k01111\cdots)_2 \text{ and } (0.a_0a_1 \cdots a_k10000\cdots)_2
\]

denote the same real number, so \( f_0 \) is not injective.

We modify \( f_0 \) so that we don’t obtain any binary numbers of the form

\[
(0.a_0a_1 \cdots a_k01111\cdots)_2
\].
Proof of Lemma 2.16 (d)

Define instead

\[ f : F \to \mathbb{R} , \]
\[ f(g) := (0.g(0) 0 g(1) 0 g(2) 0 \cdots)_2 , \]

So

\[ f(g) = (0.a_0a_1a_2 \cdots)_2 \]

where

\[ a_k := \begin{cases} 0 & \text{if } k \text{ is odd,} \\ g\left(\frac{k}{2}\right) & \text{otherwise.} \end{cases} \]
Proof of Lemma 2.16 (d)

If two sequences

\[(b_0, b_1, b_2, \ldots) \text{ and } (c_0, c_1, c_2, \ldots)\]

do not end in

\[1, 1, 1, 1, \ldots,\]

i.e. are not of the form

\[(d_0, d_1, \ldots, d_l, 1, 1, 1, 1, 1, \ldots)\]

then one can easily see that

\[(0.b_0b_1\cdots)_2 = (0.c_0c_1\cdots)_2 \iff (b_0, b_1, b_2, \ldots) = (c_0, c_1, c_2, \ldots)\]
Proof of Lemma 2.16 (d)

Therefore

\[ f(g) = f(g') \]
\[ \iff (0.g(0) \ 0 \ g(1) \ 0 \ g(2) \ 0 \cdots)_2 = (0.g'(0) \ 0 \ g'(1) \ 0 \ g'(2) \ 0 \cdots)_2 \]
\[ \iff (g(0), \ 0, \ g(1), \ 0, \ g(2), \ 0, \ldots) = (g'(0), \ 0, \ g'(1), \ 0, \ g'(2), \ 0, \ldots) \]
\[ \iff (g(0), \ g(1), \ g(2), \ldots) = (g'(0), \ g'(1), \ g'(2), \ldots) \]
\[ \iff g = g' \]

\( f \) is injective.
Lemma 2.17

(a) If $A$, $B$ are countable, so is $A \cup B$.
(b) If $A$ is uncountable and $B$ is countable then $A \setminus B$ is uncountable.

Note that

(a) reads: If two sets are small, their union is small as well.
(b) reads: If one removes from a big set a small set, then what remains is still big.
Proof of Lemma 2.17 (a)

To be shown: If $A, B$ are countable, so is $A \cup B$.

We will use the fact that a set $X$ is countable if and only if it is empty or there exist a surjective function $f : \mathbb{N} \rightarrow X$.

Therefore we need to treat the special cases when $A$ or $B$ are empty.

Case 1: $A$ is empty.
Then $A \cup B = B$ which is countable.

Case 2: $B$ is empty.
Then $A \cup B = A$ which is countable.
Proof of Lemma 2.17 (a)

Case 3: $A, B$ are not empty.

By $A, B$ countable there exist surjective functions

$$f : \mathbb{N} \to A \quad g : \mathbb{N} \to B$$

Define $h : \mathbb{N} \to A \cup B,$

$$h(n) := \begin{cases} f\left(\frac{n}{2}\right) & \text{if } n \text{ is even,} \\ g\left(\frac{n-1}{2}\right) & \text{if } n \text{ is odd.} \end{cases}$$

So $f(n) = h(2n)$ and $g(n) = h(2n + 1)$. Therefore

$$A \cup B = f[\mathbb{N}] \cup g[\mathbb{N}] \subseteq h[\mathbb{N}]$$

$f$ is surjective.
Proof of Lemma 2.17 (a)

Assume $f : \mathbb{N} \rightarrow A$, $g : \mathbb{N} \rightarrow B$. 

\[
\begin{array}{c}
\mathbb{N} \\
0 \\
1 \\
2 \\
\ldots \\
\end{array}
\xrightarrow{f} 
\begin{array}{c}
A \\
\end{array}
\]

\[
\begin{array}{c}
\mathbb{N} \\
0 \\
1 \\
2 \\
\ldots \\
\end{array}
\xrightarrow{g} 
\begin{array}{c}
B \\
\end{array}
\]
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \quad h(2n + 1) = g(n) : \]

Diagram:

- Set \( \mathbb{N} \) with elements 0, 1, 2, 3, 4, 5, 6, ... mapping to set A.
- Set \( \mathbb{N} \) with elements 0, 1, 2, ... mapping to set B.
- Function \( f \) from \( \mathbb{N} \) to A.
- Function \( g \) from \( \mathbb{N} \) to B.
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \ h(2n + 1) = g(n) : \]
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \; h(2n + 1) = g(n) : \]

\[ \begin{array}{c}
0
1
2
3
4
5
6
\ldots
\end{array} \]

\[ \begin{array}{c}
0
1
2
\ldots
\end{array} \]

\[ \begin{array}{c}
0
1
2
\ldots
\end{array} \]

\[ \begin{array}{c}
A
B
\end{array} \]

\[ f \]

\[ g \]
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \quad h(2n + 1) = g(n) : \]

\[
\begin{array}{c}
N \\
0 & 1 & 2 & 3 & 4 & 5 & 6 & \ldots \\
\end{array}
\]

\[
\begin{array}{c}
N \\
0 & 1 & 2 & \ldots \\
\end{array}
\]

\[
\begin{array}{c}
A \\
f \\
\end{array}
\]

\[
\begin{array}{c}
B \\
g \\
\end{array}
\]
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \quad h(2n + 1) = g(n) : \]
Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \quad h(2n + 1) = g(n) : \]
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\[ h(2n) = f(n), \; h(2n + 1) = g(n) : \]
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Proof of Lemma 2.17 (a)

\[ h(2n) = f(n), \quad h(2n + 1) = g(n). \]
Alternative Proof of Lemma 2.17 (a)

To be shown: If $A, B$ are countable, so is $A \cup B$.

So assume $A, B$ are countable.

Then there exist (by Lemma 2.11) injective functions

$$f : A \to \mathbb{N}, \quad g : B \to \mathbb{N}.$$ 

Define

$$h : A \cup B \to \mathbb{N},$$

$$h(x) := \begin{cases} f(x) \cdot 2 & \text{if } x \in A \\ g(x) \cdot 2 + 1 & \text{if } x \in B \setminus A \end{cases}$$

$h$ is injective.

Therefore, by Lemma 2.11, $A \cup B$ is countable.
Proof of Lemma 2.17 (b)

To be shown:
If \( A \) is uncountable and \( B \) is countable, then \( A \setminus B \) is uncountable.

Assume \( A \) is uncountable, \( B \) is countable and \( A \setminus B \) were countable.

Then \( A \cap B \) is countable (since \( A \cap B \subseteq B \)).

Therefore \( A = (A \setminus B) \cup (A \cap B) \) is countable as well, a contradiction.
Proof of Lemma 2.17 (b)

If $A \setminus B$ is countable, then $A \cap B$ is countable. However, if $A$ is uncountable, there is a contradiction. Therefore, $A \setminus B$ cannot be countable, as required.
**Continuum Hypothesis**

**Remark:**
- One can show $\mathcal{P}(\mathbb{N}) \approx \mathbb{R}$.
- Both these sets are uncountable, so they have size bigger than $\mathbb{N}$.

**Question:** Is there a set $B$ which has size (cardinality) between $\mathbb{N}$ and $\mathbb{R}$?
- I.e. there are injections $\mathbb{N} \to B$ and $B \to \mathbb{R}$,
- but no bijections $\mathbb{N} \to B$ and $B \to \mathbb{R}$.

**Continuum Hypothesis:** There exists no such set.

Continuum Hypothesis is independent of set theory, i.e. it is neither provable nor is its negation provable.

This was one of the most important open problems in set theory for a long time.
Paul Cohen

Paul Cohen
(* 1934)
Showed that the continuum hypothesis is independent of set theory.
Goal: Reduce computability on some data types \( A \) to computability on \( \mathbb{N} \).

\( A \) could be for instance the set of strings, of matrices, of trees, of lists of strings, etc.

If we can do this, then there is need for a special definition of computability on \( A \), we can concentrate on the notion of computability on \( \mathbb{N} \).

We can reduce computability on \( A \) to computability on \( \mathbb{N} \), if we have two intuitively computeable functions

- \( \text{encode}_A : A \to \mathbb{N} \),
- \( \text{decode}_A : \mathbb{N} \to A \).
Reduction of Computability to $\mathbb{N}$

- $\text{encode}_A : A \rightarrow \mathbb{N}$, $\text{decode}_A : \mathbb{N} \rightarrow A$.
- Assume we have such functions $\text{encode}_A$, $\text{decode}_A$, $\text{encode}_B$, $\text{decode}_B$ for $A$ and $B$.
- Then from an intuitively computable $f : A \rightarrow B$ we can obtain an intuitively computable function

$$\tilde{f} := \text{encode}_B \circ f \circ \text{decode}_A : \mathbb{N} \rightarrow \mathbb{N}$$
Reduction of Computability to $\mathbb{N}$

In order to recover $f$ from $\tilde{f}$, we need

$$\text{decode}_A(\text{encode}_A(a)) = a, \quad \text{decode}_B(\text{encode}_B(b)) = b,$$

i.e.

$$\text{decode}_A \circ \text{encode}_A = \text{id}_A, \quad \text{decode}_B \circ \text{encode}_B = \text{id}_B.$$

Then

$$\text{decode}_B \circ \tilde{f} \circ \text{encode}_A$$

$$= \text{decode}_B \circ \text{encode}_B \circ f \circ \text{decode}_A \circ \text{encode}_A$$

$$= f$$

so if $\tilde{f}$ is computable, so is $f$ as well.
Recovering $f$ from $\tilde{f}$

\[ \tilde{f} = \text{encode}_B \circ f \circ \text{decode}_A : \mathbb{N} \to \mathbb{N} \]

therefore

\[ \text{decode}_B \circ \tilde{f} \circ \text{encode}_A \]

\[ = \text{decode}_B \circ \text{encode}_B \circ f \circ \text{decode}_A \circ \text{encode}_A \]

\[ = f \]
Informal Definition

A data type $A$ has a **computable encoding into** $\mathbb{N}$, if there exist in an intuitive sense computable functions

$$
\text{encode}_A : A \rightarrow \mathbb{N}, \quad \text{and} \quad \text{decode}_A : \mathbb{N} \rightarrow A
$$

such that for all $a \in A$ we have

$$\text{decode}_A(\text{encode}_A(a)) = a$$
Computable Encodings

\[ \text{decode}_A(\text{encode}_A(a)) = a \]

- Note that by the above we obtain \( \text{encode}_A \) is injective.
  - In general we have for two functions \( f : B \to C \), \( g : C \to D \) that if \( g \circ f \) is injective, then \( f \) is injective as well.

- Therefore if \( A \) has a computable encoding into \( \mathbb{N} \), then there exists an injection \( \text{encode}_A : A \to \mathbb{N} \), therefore \( A \) is countable.
Remark

- We do not require

\[ \text{encode}_A(\text{decode}_A(n)) = n \]

for every \( n \in \mathbb{N} \).

- Every \( a \in A \) has a unique code in \( \mathbb{N} \),
  - i.e. \( \text{encode}_A \) is injective,
  - expressed by \( \text{decode}_A(\text{encode}_A(a)) = a \).

- But not every \( n \in \mathbb{N} \) needs to be a code for an element of \( A \),
  - \( \text{encode}_A \) needs not be surjective.
Extension of the Encoding

- We want to show that we have computable encodings of more complex data types into $\mathbb{N}$.
- Assume $A$ and $B$ have computable encodings into $\mathbb{N}$.
- Then we will show that the same applies to
  - $A \times B$, the product of $A$ and $B$,
  - $A^k$, the set of $k$-tuples of $A$,
  - $A^*$, the set of lists (or sequences) of elements of $A$.
- The proof will show as well that if $A$, $B$ are countable, so are
  \[ A \times B \ , \ A^k \ , \ A^* \ . \]
In order to show that $A \times B$, $A^k$, $A^*$ have computable encodings into $\mathbb{N}$, if $A$, $B$ have, it suffices to show that

$$\mathbb{N} \times \mathbb{N}, \mathbb{N}^n, \mathbb{N}^*,$$

have computable encodings into $\mathbb{N}$.

Note that $\mathbb{N}^2 = \mathbb{N} \times \mathbb{N}$. 
Reduction to $\mathbb{N}$

In order to see this assume we had already shown that

$$\mathbb{N}^n, \mathbb{N}^*,$$

have computable encodings, so we have computable injections

$$\text{encode}_{\mathbb{N}^n} : \mathbb{N}^n \rightarrow \mathbb{N},$$
$$\text{encode}_{\mathbb{N}^*} : \mathbb{N}^* \rightarrow \mathbb{N}.$$

with corresponding computable decoding functions.

Assume $A, B$ have computable with encodings

$$\text{encode}_A : A \rightarrow \mathbb{N},$$
$$\text{encode}_B : B \rightarrow \mathbb{N}.$$
Reduction to $\mathbb{N}$

Then we obtain a computable encoding

$$
\text{encode}_{A \times B} : (A \times B) \rightarrow \mathbb{N}
$$

$$
\text{encode}_{A \times B}((a, b)) = \text{encode}_{\mathbb{N}^2}((\text{encode}_A(a), \text{encode}_B(b)))
$$

In short

$$
\text{encode}_{A \times B}((a, b)) = \text{encode}_{\mathbb{N}^2}((\text{encode}_A(a), \text{encode}_B(b)))
$$

**Exercise:** Define $\text{decode}_{A \times B}$, show $\text{decode}_{A \times B}(\text{encode}_{A \times B}(x)) = x$ and verify that $\text{decode}_{A \times B}$ is intuitively computable.
Reduction to $\mathbb{N}$

$$
\text{encode}_{A^k} : A^k \rightarrow \mathbb{N}
$$

$$
\text{encode}_{A^k}((a_0, \ldots, a_{k-1})) =
\text{encode}_{\mathbb{N}^k}((\text{encode}_A(a_0), \text{encode}_A(a_1), \ldots, \text{encode}_A(a_{k-1})))
$$

In short

$$
\text{encode}_{A^k}((a_0, \ldots, a_{k-1})) =
\text{encode}_{\mathbb{N}^k}((\text{encode}_A(a_0), \text{encode}_A(a_1), \ldots, \text{encode}_A(a_{k-1})))
$$

Exercise: Define $\text{decode}_{A^k}$, show $\text{decode}_{A^k}(\text{encode}_{A^k}(x)) = x$

and verify that $\text{decode}_{A^k}$ is intuitively computable.
Reduction to $\mathbb{N}$

We obtain a computable encoding

$$
\text{encode}_{A^*} : A^* \rightarrow \mathbb{N}
$$

$$
\text{encode}_{A^*}((a_0, \ldots, a_{n-1})) =
\text{encode}_{\mathbb{N}^*}((\text{encode}_A(a_0), \text{encode}_A(a_1), \ldots, \text{encode}_A(a_{n-1})))
$$

In short

$$
\text{encode}_{A^*}((a_0, \ldots, a_{n-1})) =
\text{encode}_{\mathbb{N}^*}((\text{encode}_A(a_0), \text{encode}_A(a_1), \ldots, \text{encode}_A(a_{n-1})))
$$

Exercise: Define $\text{decode}_{A^*}$, show $\text{decode}_{A^*}(\text{encode}_{A^*}(x)) = x$ and verify that $\text{decode}_{A^*}$ is intuitively computable.
Encoding of Pairs

- The first step is to give a computable encoding of $\mathbb{N}^2$ into $\mathbb{N}$.
- In fact our encoding will be a bijection.
- We will define intuitively computable functions

\[
\pi : \mathbb{N}^2 \rightarrow \mathbb{N}
\]
\[
\pi_0 : \mathbb{N} \rightarrow \mathbb{N}
\]
\[
\pi_1 : \mathbb{N} \rightarrow \mathbb{N}
\]

s.t. $\pi$ and

\[
\lambda n. (\pi_0(n), \pi_1(n)) : \mathbb{N} \rightarrow \mathbb{N}^2
\]

are inverse to each other.
Encoding of Pairs

\[ \pi : \mathbb{N}^2 \to \mathbb{N} \]
\[ \pi_0 : \mathbb{N} \to \mathbb{N} \]
\[ \pi_1 : \mathbb{N} \to \mathbb{N} \]

Therefore we obtain a computable encoding of \( \mathbb{N} \times \mathbb{N} \) into \( \mathbb{N} \) with

\[
\text{encode}_{\mathbb{N} \times \mathbb{N}} := \pi : \mathbb{N}^2 \to \mathbb{N}
\]
\[
\text{decode}_{\mathbb{N} \times \mathbb{N}} := \lambda x. (\pi_0(x), \pi_1(x)) : \mathbb{N} \to \mathbb{N}^2
\]
Encoding of Pairs

\( \pi \) will be called the \textit{pairing function} and \( \pi_i \) the \textit{projection functions} or short \textit{projections}. \( \pi \) is a computable encoding of \( \mathbb{N}^2 \) into \( \mathbb{N} \).
Definition of $\pi$

Pairs of natural numbers can be enumerated in the following way:

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<tr>
<th>$y$</th>
<th>0</th>
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</table>
### Definition of $\pi$

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</table>

$\pi(0, 0) = 0$, $\pi(1, 0) = 1$, $\pi(0, 1) = 2$, $\pi(2, 0) = 3$, $\pi(1, 1) = 4$, $\pi(0, 2) = 5$, etc.
Attempt which fails

Note, that the following naïve attempt to enumerate the pairs, fails:

\[
\begin{array}{c|cccc}
 y & 0 & 1 & 2 & 3 \\
\hline
 x & \pi(0,0) & \pi(0,1) & \pi(0,2) & \pi(0,3) \\
0 & \rightarrow & \rightarrow & \rightarrow & \rightarrow \\
1 & \rightarrow & \rightarrow & \rightarrow & \rightarrow \\
2 & \rightarrow & \rightarrow & \rightarrow & \rightarrow \\
3 & \rightarrow & \rightarrow & \rightarrow & \rightarrow \\
4 & \rightarrow & \rightarrow & \rightarrow & \rightarrow \\
\end{array}
\]

\[\pi(0,0) = 0, \ \pi(0,1) = 1, \ \pi(0,2) = 2, \ \text{etc.}\]

We never reach the pair \((1,0)\).
In the following we are going to develop a mathematical formula for $\pi$.

In the lecture this material was omitted and we give directly the definition of $\pi$.

Jump over Development of $\pi$. 
Definition of $\pi$

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For the pairs in the diagonal we have the property that $x + y$ is constant.
Definition of $\pi$

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For the pairs in the diagonal we have the property that $x + y$ is constant.
For the pairs in the diagonal we have the property that $x + y$ is constant.
The first diagonal, consisting of $(0, 0)$ only, is given by

\[ x + y = 0. \]
For the pairs in the diagonal we have the property that $x + y$ is constant. The second diagonal, consisting of $(1, 0), (0, 1)$, is given by $x + y = 1$. 
Definition of $\pi$

For the pairs in the diagonal we have the property that $x + y$ is constant.
The third diagonal, consisting of $(2,0), (1,1), (0,2)$, is given by $x + y = 2$. 

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For the pairs in the diagonal we have the property that $x + y$ is constant.
The third diagonal, consisting of $(2, 0), (1, 1), (0, 2)$, is given by $x + y = 2$.
Etc.
**Definition of** $\pi$

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If we look in the original approach at the diagonals we see that following:

- The diagonal given by $x + y = n$, consists of $n + 1$ pairs:
Definition of $\pi$

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Definition of $\pi$ 

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If we look in the original approach at the diagonals we see that following:

- The diagonal given by \( x + y = n \), consists of \( n + 1 \) pairs:
- The first diagonal, given by \( x + y = 0 \), consists of \((0, 0)\) only, i.e. of 1 pair.
## Definition of $\pi$

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If we look in the original approach at the diagonals we see that following:

- The diagonal given by $x + y = n$, consists of $n + 1$ pairs:
- The second diagonal, given by $x + y = 1$, consists of $(1, 0), (0, 1)$, i.e. of 2 pairs.
Definition of $\pi$

If we look in the original approach at the diagonals we see that following:

- The diagonal given by $x + y = n$, consists of $n + 1$ pairs:
  - The third diagonal, given by $x + y = 2$, consisting of $(2, 0), (1, 1), (0, 2)$, i.e. of 3 pairs.
**Definition of** \( \pi \)

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If we look in the original approach at the diagonals we see that following:

- The diagonal given by \( x + y = n \), consists of \( n + 1 \) pairs:
  - The third diagonal, given by \( x + y = 2 \), consisting of \((2, 0), (1, 1), (0, 2)\), i.e. of 3 pairs.
- etc.
We count the elements occurring before the pair \((x_0, y_0)\).

We have to count all elements of the previous diagonals. These are those given by \(x + y = n\) for \(n < x_0 + y_0\).

In the above example for the pair \((2, 1)\), these are the diagonals given by \(x + y = 0, x + y = 1, x + y = 2\).
The diagonal, given by $x + y = n$, has $n + 1$ elements, so in total we have

$$\sum_{i=0}^{x+y-1} (i + 1) = 1 + 2 + \cdots + (x + y) = \sum_{i=1}^{x+y} i$$

elements in those diagonals.

A often used formula says $\sum_{i=1}^{n} i = \frac{n(n+1)}{2}$. Therefore, the above is $\frac{(x+y)(x+y+1)}{2}$.
Definition of $\pi$

<table>
<thead>
<tr>
<th>$y$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td></td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Further, we have to count all pairs in the current diagonal, which occur in this ordering before the current one. These are $y$ pairs.

- Before $(2, 1)$ there is only one pair, namely $(3, 0)$.
- Before $(3, 0)$ there are 0 pairs.
- Before $(0, 2)$ there are 2 pairs, namely $(2, 0), (1, 1)$. 
Therefore we get that there are in total \( \frac{(x+y)(x+y+1)}{2} + y \) pairs before \((x, y)\), therefore the pair \((x, y)\) is the pair number \( \left( \frac{(x+y)(x+y+1)}{2} + y \right) \) in this order.
Definition of \( \pi \)

Definition 2.18

\[
\pi(x, y) := \frac{(x + y)(x + y + 1)}{2} + y \quad (= \left( \sum_{i=1}^{x+y} i \right) + y)
\]

Exercise: Prove that \( \sum_{i=1}^{n} i = \frac{n(n+1)}{2} \).
Lemma 2.19

\( \pi \) is bijective.

Omit Proof
Proof of Bijectivity of $\pi$

We show $\pi$ is injective:
We prove first that, if $x + y < x' + y'$, then $\pi(x, y) < \pi(x', y')$:

$$
\pi(x, y) = \left( \sum_{i=1}^{x+y} i \right) + y < \left( \sum_{i=1}^{x+y} i \right) + x + y + 1 = \sum_{i=1}^{x+y+1} i
$$

$$
\leq \left( \sum_{i=1}^{x'+y'} i \right) + y' = \pi(x', y')
$$
Proof of Bijectivity of $\pi$

We show $\pi$ is injective:
Assume now $\pi(x, y) = \pi(x', y')$ and show $x = x'$ and $y = y'$. We have by the above

$$x + y = x' + y'.$$

Therefore

$$y = \pi(x, y) - \left( \sum_{i=1}^{x+y} i \right) = \pi(x', y') - \left( \sum_{i=1}^{x'+y'} i \right) = y'$$

and

$$x = (x + y) - y = (x' + y') - y' = x'.$$
Proof of Bijectivity of \( \pi \)

We show \( \pi \) is surjective:

Assume \( n \in \mathbb{N} \).

Show \( \pi(x, y) = n \) for some \( x, y \in \mathbb{N} \).

The sequence \( (\sum_{i=1}^{k'} i)_{k' \in \mathbb{N}} \) is strictly existing.

Therefore there exists a \( k \) s.t.

\[
\begin{align*}
\sum_{i=1}^{k} i & \leq n < \sum_{i=1}^{k+1} i \\
\end{align*}
\]
Proof of Bijectivity of $\pi$

$n \in \mathbb{N}$
Show $\pi(x, y) = n$ for some $x, y$

$$a := \sum_{i=1}^{k} i \leq n < \sum_{i=1}^{k+1} i$$

So, in order to obtain $\pi(x, y) = n$, we need $x + y = k$.
By $y = \pi(x, y) - \sum_{i=1}^{x+y} i$, we need to define $y := n - a$.
By $k = x + y$, we need to define $x := k - y$.
By (*) it follows $0 \leq y < k + 1$,
therefore $x, y \geq 0$. Further,
$\pi(x, y) = (\sum_{i=1}^{x+y} i) + y = (\sum_{i=1}^{k} i) + (n - \sum_{i=1}^{k} i) = n$. 
Definition of $\pi_0$, $\pi_1$

Since $\pi$ is bijective, we can define $\pi_0$, $\pi_1$ as follows:

**Definition 2.20**

Let $\pi_0 : \mathbb{N} \rightarrow \mathbb{N}$ and $\pi_1 : \mathbb{N} \rightarrow \mathbb{N}$ be s.t.

$$\pi_0(\pi(x, y)) = x, \quad \pi_1(\pi(x, y)) = y.$$
Remark

\( \pi, \pi_0, \pi_1 \) are computable in an intuitive sense.

“Proof:”

\( \pi \) is obviously computable.

In order to compute \( \pi_i(n) \), one first observes

\[
\frac{(x+y)(x+y+1)}{2} \leq \pi(x, y) = \frac{(x+y)(x+y+1)}{2} + y \\
< \frac{(x+y)(x+y+1)}{2} + (x + y + 1) \\
= \frac{(x+y+2)(x+y+1)}{2} \\
= \frac{(x+y+1)(x+y+2)}{2}
\]
Proof of $\pi_i$ Computable

\[
\frac{(x+y)(x+y+1)}{2} \leq \pi(x, y) < \frac{(x+y+1)(x+y+2)}{2}
\]

- If we define for $n$

  \[
k(n) = \max\{k \mid \frac{k(k+1)}{2} \leq n\}
  \]

  which is intuitively computable, we obtain if $\pi(x, y) = n$, then $k(n) = x + y$.

- But then $\pi(x, y) = \frac{k(n)(k(n)+1)}{2} + y$, therefore, if $n = \pi(x, y)$, then we have

  \[
  \pi_1(n) = y = \pi(x, y) - \frac{k(n)(k(n)+1)}{2} = n - \frac{k(n)(k(n)+1)}{2}
  \]
Proof of $\pi_i$ Computable

\[
\frac{(x+y)(x+y+1)}{2} \leq \pi(x, y) < \frac{(x+y+1)(x+y+2)}{2}
\]

$\pi_1(n) = n - \frac{k(n)(k(n)+1)}{2}$

Then we have

\[
\begin{align*}
\pi_0(n) &= x \\
&= k(n) - y \\
&= k(n) - \pi_1(n)
\end{align*}
\]

This gives a method for computing $\pi_0(n)$, $\pi_1(n)$, so $\pi_0(n)$, $\pi_1(n)$ are intuitively computable.
For all \( z \in \mathbb{N} \),
\[
\pi(\pi_0(z), \pi_1(z)) = z .
\]

Proof:
Assume \( z \in \mathbb{N} \) and show
\[
z = \pi(\pi_0(z), \pi_1(z)) .
\]
\( \pi \) is surjective, so there exists \( x, y \) s.t.
\[
\pi(x, y) = z .
\]
Then
\[
\pi(\pi_0(z), \pi_1(z)) = \pi(\pi_0(\pi(x, y)), \pi_1(\pi(x, y))) = \pi(x, y) = z .
\]
Encoding of $\mathbb{N}^k$

- We want to encode $\mathbb{N}^k$ into $\mathbb{N}$.
- $(l, m, n) \in \mathbb{N}^3$ can be encoded as follows
  - First encode $(l, m)$ as $\pi(l, m) \in \mathbb{N}$.
  - Then encode the complete triple as $\pi(\pi(l, m), n) \in \mathbb{N}$.
- So define $\pi^3(l, m, n) := \pi(\pi(l, m), n)$.
- Similarly $(l, m, n, p) \in \mathbb{N}^4$ can be encoded as follows:
  $$\pi^4(l, m, n, p) := \pi(\pi(\pi(l, m), n), p).$$
Decoding Function

If \( x = \pi^3(l, m, n) = \pi(\pi(l, m), n) \), then we see

\[
\begin{align*}
  l & = \pi_0(\pi_0(x)), \\
  m & = \pi_1(\pi_0(x)), \\
  n & = \pi_1(x).
\end{align*}
\]

So we define

\[
\begin{align*}
  \pi^3_0(x) & = \pi_0(\pi_0(x)), \\
  \pi^3_1(x) & = \pi_1(\pi_0(x)), \\
  \pi^3_2(x) & = \pi_1(x).
\end{align*}
\]
Decoding Function

Similarly, if \( x = \pi^4(l, m, n, p) = \pi(\pi(l, m), n, p) \), then we see

- \( l = \pi_0(\pi_0(\pi_0(x))) \),
- \( m = \pi_1(\pi_0(\pi_0(x))) \),
- \( n = \pi_1(\pi_0(x)) \).
- \( p = \pi_1(x) \).

So we define

- \( \pi_0^4(x) = \pi_0(\pi_0(\pi_0(\pi_0(x)))) \),
- \( \pi_1^4(x) = \pi_1(\pi_0(\pi_0(\pi_0(x)))) \),
- \( \pi_2^4(x) = \pi_1(\pi_0(x)) \).
- \( \pi_3^4(x) = \pi_1(x) \).
In general one defines for \( k \geq 1 \)

\[
\pi^k : \mathbb{N}^k \rightarrow \mathbb{N} , \\
\pi^k(x_0, \ldots, x_{k-1}) := \pi(\cdots \pi(\pi(x_0, x_1), x_2) \cdots x_{k-1} ) ,
\]

and for \( i < k \)

\[
\pi_i^k : \mathbb{N} \rightarrow \mathbb{N} , \\
\pi_0^k(x) := \pi_0(\cdots \pi_0(x) \cdots) , \quad k - 1 \text{ times} \\
\text{and for } 0 < i < k, \\
\pi_i^k(x) := \pi_1(\pi_0(\pi_0(\cdots \pi_0(x) \cdots )))) , \quad k - i - 1 \text{ times}
\]
Formal definition of $\pi^k_i$, $\pi^k_i$

Then $\pi^k_i$ and

$$\lambda x. (\pi^k_0(x), \ldots, \pi^k_{k-1}(x))$$

are inverse to each other.

A formal inductive Definition of $\pi^k_i$ and $\pi^k_i$ is as follows: Jump over formal definition of $\pi$
Definition 2.22 of $\pi^k, \pi_i^k$

(a) We define by induction on $k$ for $k \in \mathbb{N}, k \geq 1$

$$\pi^k : \mathbb{N}^k \rightarrow \mathbb{N}$$

$$\pi^1(x) := x$$

For $k > 0$:

$$\pi^{k+1}(x_0, \ldots, x_k) := \pi(\pi^k(x_0, \ldots, x_{k-1}), x_k)$$

(b) We define by induction on $k$ for $i, k \in \mathbb{N}$ s.t. $1 \leq k,$ $0 \leq i < k$:

$$\pi_i^k : \mathbb{N} \rightarrow \mathbb{N}$$

$$\pi_0^1(x) := x$$

$$\pi_{i+1}^k(x) := \pi_i^k(\pi_0(x)) \text{ for } i < k$$

$$\pi_{k+1}^k(x) := \pi_1(x)$$

Omit Examples.
Examples

\[ \pi^2(x, y) = \pi(\pi^1(x), y) = \pi(x, y). \]

\[ \pi^3(x, y, z) = \pi(\pi^2(x, y), z) = \pi(\pi(x, y), z). \]

\[ \pi^4(x, y, z, u) = \pi(\pi^3(x, y, z), u) = \pi(\pi(\pi(x, y), z), u). \]

\[ \pi^0_4(u) = \pi^3_0(\pi^0_0(u)) = \pi^2_0(\pi^0_0(\pi^0_0(u))) = \pi^1_0(\pi^0_0(\pi^0_0(\pi^0_0(u)))) = \pi_0(\pi_0(\pi_0(u))). \]

\[ \pi^4_2(u) = \pi^3_2(\pi^0_0(u)) = \pi_1(\pi^0_0(u)). \]
Lemma 2.23

(a) For $(x_0, \ldots, x_{k-1}) \in \mathbb{N}^k, i < k, x_i = \pi^k_i (\pi^k (x_0, \ldots, x_{k-1})).$

(b) For $x \in \mathbb{N}, x = \pi^k (\pi^k_0 (x), \ldots, \pi^k_{k-1} (x)).$

(Omit Proof)
Proof

Induction on \( k \).

**Base case** \( k = 0 \):

**Proof of (a):**

Let \((x_0) \in \mathbb{N}^1\).

Then \( \pi_0^1(\pi^1(x_0)) = x_0 \).

**Proof of (b):**

Let \( x \in \mathbb{N} \).

Then \( \pi^1(\pi_0^1(x)) = x \).
Proof of Lemma 2.23

**Induction step** $k \rightarrow k + 1$:
Assume the assertion has been shown for $k$.

**Proof of (a):**
Let $(x_0, \ldots, x_k) \in \mathbb{N}^{k+1}$.
Then

$$\begin{align*}
\text{for } i &< k & \pi_i^{k+1}(\pi^{k+1}(x_0, \ldots, x_k)) \\
&= \pi_i^k(\pi(\pi^k(x_0, \ldots, x_{k-1}), x_k)) \\
&= \pi_i^k(\pi^k(x_0, \ldots, x_{k-1})) \\
\text{IH} &\equiv x_i
\end{align*}$$

and

$$\begin{align*}
\pi_k^{k+1}(\pi^{k+1}(x_0, \ldots, x_k)) \\
&= \pi_1(\pi(\pi^k(x_0, \ldots, x_{k-1}), x_k)) \\
&= x_k
\end{align*}$$
Proof of Lemma 2.23

Induction step $k \rightarrow k + 1$:
Assume the assertion has been shown for $k$.

Proof of (b):
Let $x \in \mathbb{N}$.

\[
\pi^{k+1}(\pi^{k+1}_0(x), \ldots, \pi^{k+1}_k(x))
\]
\[
= \pi(\pi^k(\pi^{k+1}_0(x), \ldots, \pi^{k+1}_k(x)), \pi^{k+1}_k(x))
\]
\[
= \pi(\pi^k(\pi^k_0(\pi_0(x)), \ldots, \pi^k_{k-1}(\pi^k_0(x))), \pi^k_1(x))
\]
\[
\overset{\text{IH}}{=} \pi(\pi^k_0(x), \pi^k_1(x))
\]
\[
\overset{\text{Rem. 2.21}}{=} x
\]
Encoding of $\mathbb{N}^*$

We want to define an encoding $\text{encode}_{\mathbb{N}^*} : \mathbb{N}^* \rightarrow \mathbb{N}$ (which will be a bijection).

$\mathbb{N}^* = \mathbb{N}^0 \cup \bigcup_{n \geq n} \mathbb{N}^n$.

$\mathbb{N}^0 = \{\langle \rangle\}$,

We can encode $\langle \rangle$ as 0.

Encoding of $\bigcup_{n \geq n} \mathbb{N}^n$:

We have an encoding

$$\pi^k : \mathbb{N}^k \rightarrow \mathbb{N}.$$
Encoding of $\mathbb{N}^*$

- Note that each $n \in \mathbb{N}$ is a code for elements of $\mathbb{N}^k$ for every $k$.

- So if we encoded $\langle n_0, \ldots, n_{k-1} \rangle$ as $\pi^k(n_0, \ldots, n_{k-1})$ we couldn’t determine the length $k$ of the original sequence from the code.

- So we need to add the length to the code for $(n_0, \ldots, n_{k-1})$ (considered as an element of $\mathbb{N}^*$).

- Therefore encode a sequence $(n_0, \ldots, n_{k-1}) \in \mathbb{N}^*$ for $k > 0$ as

$$\pi(k - 1, \pi^k(n_0, \ldots, n_{k-1})) .$$

- In order to distinguish it from code of $\langle \rangle$, add 1 to it.

- In total we obtain a bijection.
Definition 2.24 of $\langle \rangle$, $lh$, $(x)_i$

(a) Define for $x \in \mathbb{N}^*$, $\langle x \rangle : \mathbb{N}$ as follows:

$$\langle \rangle := 0 ,$$

for $k > 0$

$$\langle (n_0, \ldots, n_{k-1}) \rangle := \langle n_0, \ldots, n_k \rangle := 1 + \pi(k, \pi^{k+1}(n_0, \ldots, n_k))$$

(b) Define for $x \in \mathbb{N}$, the length $\langle x \rangle \in \mathbb{N}$ as follows:

$$lh : \mathbb{N} \rightarrow \mathbb{N} ,$$

$$lh(0) := 0 ,$$

$$lh(x) := \pi_0(x - 1) + 1 \text{ if } x > 0 .$$
Definition 2.24 of $\langle \rangle$, $\text{lh}$, $(x)_i$

(c) We define for $x \in \mathbb{N}$ and $i < \text{lh}(x)$, the $i$th component

$$(x)_i \in \mathbb{N}$$

of a code $x$ for a sequence as follows:

$$(x)_i := \pi_{\text{lh}(x)}(\pi_1(x - 1)) .$$

For $\text{lh}(x) \leq i$, let

$$(x)_i := 0 .$$
Lemma 2.25

Lemma 2.25

(a) \( \text{lh}(\langle \rangle) = 0, \quad \text{lh}(\langle n_0, \ldots, n_k \rangle) = k + 1. \)

(b) For \( i \leq k, \) \( (\langle n_0, \ldots, n_k \rangle)_i = n_i. \)

(c) For \( x \in \mathbb{N}, \) \( x = \langle (x)_0, \ldots, (x)_{\text{lh}(x) - 1} \rangle. \)

(Omit Proof)
Proof of Lemma 2.25 (a)

Proof of (a):

Show: \( \text{lh}(\langle \rangle) = 0 \):
\[
\text{lh}(\langle \rangle) = \text{lh}(0) = 0.
\]

Show: \( \text{lh}(\langle n_0, \ldots, n_k \rangle) = k + 1 \):
\[
\begin{align*}
\text{lh}(\langle n_0, \ldots, n_k \rangle) &= \pi_0(\langle n_0, \ldots, n_k \rangle - 1) + 1 \\
&= \pi_0(\pi(k, \cdots) + 1 - 1) + 1 \\
&= k + 1
\end{align*}
\]
Proof of Lemma 2.25 (b)

Proof of (b):
Show \((\langle n_0, \ldots, n_k \rangle)_i = n_i\).
\(lh(\langle n_0, \ldots, n_k \rangle) = k + 1\).
Therefore

\[
\begin{align*}
(\langle n_0, \ldots, n_k \rangle)_i &= \pi_i^{k+1}(\pi_1(\langle n_0, \ldots, n_k \rangle - 1)) \\
&= \pi_i^{k+1}(\pi_1(1 + \pi(k, \pi^{k+1}(n_0, \ldots, n_k)) - 1)) \\
&= \pi_i^{k+1}(\pi^{k+1}(n_0, \ldots, n_k)) \\
&= n_i
\end{align*}
\]
Proof of Lemma 2.25 (c)

Proof of (c):
Show \( x = \langle (x)_0, \ldots, (x)_{\text{lh}(x)-1} \rangle \).

**Case** \( x = 0 \).
\( \text{lh}(x) = 0 \). Therefore \( \langle (x)_0, \ldots, (x)_{\text{lh}(x)-1} \rangle = \langle \rangle = 0 = x \).

**Case** \( x > 0 \).
Let \( x - 1 = \pi(l, y) \).
Then \( \text{lh}(x) = l + 1 \), \( (x)_i = \pi^{l+1}_i(y) \) and therefore

\[
\begin{align*}
\langle (x)_0, \ldots, (x)_{\text{lh}(x)-1} \rangle & = \langle \pi^{l+1}_0(y), \ldots, \pi^{l+1}_l(y) \rangle \\
& = \pi(l, \pi^{l+1}(\pi^{l+1}_0(y), \ldots, \pi^{l+1}_l(y))) + 1 \\
& \overset{\text{Lem 2.23 (b)}}{=} \pi(l, y) + 1 \\
& = x
\end{align*}
\]
Informal Lemma

If $A$ is a finite non-empty set, then $A$ and $A^*$ have computables encoding into $\mathbb{N}$. 
Proof of the Informal Lemma

Assume

\[ A = \{a_0, \ldots, a_n\} \]

where \( a_i \neq a_j \) for \( i \neq j \), \( n \geq 0 \).

Define

\[ \text{encode}_A : A \rightarrow \mathbb{N} \]

\[ f(a_i) = i . \]

Define

\[ \text{decode}_A : \mathbb{N} \rightarrow A \]

\[ \text{decode}_A(i) := a_i \text{ if } i \leq n \]

\[ \text{decode}_A(i) := a_0 \text{ if } i > n . \]
Proof of the Informal Lemma

- \( \text{encode}_A \) and \( \text{decode}_A \) are in an intuitive sense computable, and

\[
\text{decode}_A(\text{encode}_A(a)) = a
\]

- Therefore \( A \) has a computable encoding into \( \mathbb{N} \),
- Therefore \( A^* \) has as well a computable encoding into \( \mathbb{N} \).

**Remark:** One easily sees that the encoding obtained by this proof is

\[
\begin{align*}
\text{encode}_{A^*} &: A^* \to \mathbb{N} , \\
\text{encode}_{A^*}(a_0, \ldots, a_n) &= \langle \text{encode}_A(a_0), \ldots, \text{encode}_A(a_n) \rangle
\end{align*}
\]
Theorem 2.26

(a) $\mathbb{N}^k$ and $\mathbb{N}^*$ are countable.
(b) If $A$ is countable, so are $A^k$, $A^*$.
(c) If $A$, $B$ are countable, so is $A \times B$.
(d) If $A_n$ are countable sets for $n \in \mathbb{N}$, so is $\bigcup_{n \in \mathbb{N}} A_n$.
(e) $\mathbb{Q}$, the set of rational numbers, is countable.
Proof of Theorem 2.26 (a)

- $\mathbb{N}^0 = \{()\}$ is finite therefore countable.
- For $k > 0$
  \[
  \pi^k : \mathbb{N}^k \rightarrow \mathbb{N}
  \]
  is a bijection.
- The function
  \[
  \lambda x. \langle x \rangle : \mathbb{N}^* \rightarrow \mathbb{N}
  \]
  is a bijection.
Proof of Theorem 2.26 (b)

- Assume $A$ is countable.
- We show first that $A^*$ is countable:
- There exists $\text{encode}_A : A \rightarrow \mathbb{N}$, $\text{encode}_A$ injective.
- Define

\[
\begin{align*}
  f & : A^* \rightarrow \mathbb{N}^* \\
  f(a_0, \ldots, a_{k-1}) & := (\text{encode}_A(a_0), \ldots, \text{encode}_A(a_{k-1}))
\end{align*}
\]

- $f$ is injective as well, $\mathbb{N}^*$ is countable, so by Corollary 2.13 $A^*$ is countable.
- $A^k \subseteq A^*$, so $A^k$ is countable as well.
Proof of Theorem 2.26 (c)

Assume $A$, $B$ countable.

Then there exist injections

\[
\begin{align*}
\text{encode}_A & : A \rightarrow \mathbb{N} \\
\text{encode}_B & : B \rightarrow \mathbb{N}
\end{align*}
\]

Define

\[
f : (A \times B) \rightarrow \mathbb{N}^2 , \quad f(a, b) := (\text{encode}_A(a), \text{encode}_B(b))
\]

$f$ is injective, $\mathbb{N}^2$ is countable, so $A \times B$ is countable as well.
Proof of Theorem 2.26 (d)

- Assume $A_n$ are countable for $n \in \mathbb{N}$.
- Show

$$A := \bigcup_{n \in \mathbb{N}} A_n$$

is countable as well.
- If all $A_n$ are empty, so is

$$\bigcup_{n \in \mathbb{N}} A_n$$

and therefore countable.
- Assume now $A_{k_0}$ is non-empty for some $k_0$. 
Proof of Theorem 2.26 (d)

\( A_n \) are countable
Show \( \bigcup_{n \in \mathbb{N}} A_n \) is countable.

- By replacing empty \( A_l \) by \( A_{k_0} \), we get a sequence of non-empty sets \( (A_n)_{n \in \mathbb{N}} \), s.t. their union is the same as \( A \).
- So we can assume without loss of generality \( A_n \neq \emptyset \) for all \( n \).
- \( A_n \) are countable, so there exist \( f_n : \mathbb{N} \rightarrow A_n \) surjective.
Proof of Theorem 2.26 (d)

\( f_n : \mathbb{N} \rightarrow A_n \) surjective
Show \( \bigcup_{n \in \mathbb{N}} A_n \) is countable.

Then

\[
f : \mathbb{N}^2 \rightarrow A,
\]

\[
f(n, m) := f_n(m)
\]

is surjective as well.

\( \mathbb{N}^2 \) is countable, so by Corollary 2.15 \( A \) is countable as well.
Proof of Theorem 2.26 (e)

- \( \mathbb{Z} \times \mathbb{N} \) is countable, since \( \mathbb{Z} \) and \( \mathbb{N} \) are countable.
- Let
  \[
  A := \{(z, n) \in \mathbb{Z} \times \mathbb{N}, n \neq 0\}.
  \]
- \( A \subseteq \mathbb{Z} \times \mathbb{N} \), therefore \( A \) is countable as well.
- Define
  \[
  g : A \rightarrow \mathbb{Q},
  \]
  \[
  g(z, n) := \frac{z}{n}.
  \]
- \( g \) is surjective, \( A \) countable, therefore by Corollary 2.15 \( \mathbb{Q} \) is countable as well.
(f) Partial Functions

A partial function $f : A \rightsquigarrow B$ is the same as a function $f : A \rightarrow B$, but $f(a)$ might not be defined for all $a \in A$.

Key example: function computed by a computer program:

- Program has some input $a \in A$ and possibly returns some $b \in B$.
  (We assume that program does not refer to global variables).
- If the program applied to $a \in A$ terminates and returns $b$, then $f(a)$ is defined and equal to $b$.
- If the program applied to $a \in A$ does not terminate, then $f(a)$ is undefined.
Examples of Partial Functions

Other Examples:

- \( f : \mathbb{R} \rightarrow \mathbb{R} \), \( f(x) = \frac{1}{x} \):
  - \( f(0) \) is undefined.

- \( g : \mathbb{R} \rightarrow \mathbb{R} \), \( g(x) = \sqrt{x} \):
  - \( g(x) \) is defined only for \( x \geq 0 \).
Definition of Partial Functions

Definition 2.27

- Let $A$, $B$ be sets. A partial function $f$ from $A$ to $B$, written $f : A \leadsto B$, is a function $f : A' \rightarrow B$ for some $A' \subseteq A$. $A'$ is called the **domain of** $f$, written as $A' = \text{dom}(f)$.

- Let $f : A \leadsto B$.
  - $f(a)$ is defined, written as $f(a) \downarrow$, if $a \in \text{dom}(f)$.

- Let $b \in \mathbb{N}$.
  - $f(a) \simeq b$ (**$f(a)$ is partially equal to** $b$)
    
    $\iff f(a) \downarrow \land f(a) = b$. 
We want to work with terms like $f(g(2), h(3))$, where $f, g, h$ are partial functions.

**Question:** what happens if $g(2)$ or $h(3)$ is undefined?

There is a theory of partial functions, in which $f(g(2), h(3))$ might be defined, even if $g(2)$ or $h(3)$ is undefined.

Makes sense for instance for the function $f : \mathbb{N}^2 \rightarrow \mathbb{N}, f(x, y) = 0$.

Theory of such functions is more complicated.
Strict vs. Non-strict Functions

- Functions, which are defined, even if some of its arguments are undefined, are called non-strict.
- Functions, which are defined only if all of its arguments are defined are called strict.
Call-By-Value

Strict function are obtained by “call-by-value” evaluation.

Call-by-value means that before the value of a function applied to arguments, is computed, the arguments of the function are evaluated.

If we treat undefinedness as non-termination, then all functions computed by call-by-value will be strict.

There is as well finite error, e.g. the error if a division by 0 occurs. This kind of undefinedness will be handled in a non-strict way by many programming languages.

Most programming languages (including practically all imperative and object-oriented languages), use call-by-value evaluation.
Non-strict functions are obtained by “call-by-name” evaluation:

- The arguments of a function are evaluated only if they are needed in the computation of \( f \).
- Haskell uses call-by-name-evaluation.
- Therefore functions in Haskell are in general non-strict.
Example

- Let $f : \mathbb{N}^2 \sim \mathbb{N}$, $f(x, y) = x$.

- Let $t$ be an undefined term, e.g. $g(0)$, where $g : \mathbb{N} \sim \mathbb{N}$, $g(x) := g(x)$.
  - So the recursion equation of $g(x)$ doesn’t terminate.

- With call-by-need, the term $f(2, t)$ evaluates to 2, since we never need to evaluate $t$.

- With call-by-value, first $t$ is evaluated, which never terminates, so $f(2, t) \uparrow$.

- In our setting, functions are strict, so $f(2, t)$ as above is undefined.
In this lecture, functions will always be strict.

Therefore, a term like \( f(g(2), h(3)) \) is defined only, if \( g(2) \) and \( h(3) \) are defined, and if \( f \) applied to the results of evaluating \( g(2) \) and \( h(3) \) is defined.

\( f(g(2), h(3)) \) is evaluated as for ordinary functions: We first compute \( g(2) \) and \( h(3) \), and then evaluate \( f \) applied to the results of those computations.
⊥ (pronounced *bottom*) is a term which is always undefined.

So ⊥ ↓ does not hold.
Definition 2.28

For expressions $t$ formed from constants, $\bot$, variables and partial functions we define whether $t \downarrow$, and whether $t \simeq b$ holds:

- If $t = a$ is a constant, then $t \downarrow$ holds always and $t \simeq b : \iff a = b$.
- If $t = \bot$, then neither $t \downarrow$ not $t \simeq b$ do hold.
- If $t = x$ is a variable, then $t \downarrow$ holds always and $t \simeq b : \iff x = b$.

$$f(t_1, \ldots, t_n) \simeq b : \iff \exists a_1, \ldots, a_n. t_1 \simeq a_1 \land \cdots \land t_n \simeq a_n \land f(a_1, \ldots, a_n) \simeq b$$

$$f(t_1, \ldots, t_n) \downarrow : \iff \exists b. f(t_1, \ldots, t_n) \simeq b$$
Remark

- Note that variables are always considered as being defined:
  \[ x \downarrow \]

- One can easily observe
  \[ t \downarrow \iff \exists x . t \simeq x \]
Terms formed from Partial Functions

- $s \uparrow : \iff \neg (s \downarrow)$.

- We define for expressions $s, t$ formed from constants and partial functions

  $$s \simeq t : \iff (s \downarrow \leftrightarrow t \downarrow) \land (s \downarrow \rightarrow \exists a, b. s \simeq a \land t \simeq b \land a = b)$$

- $t$ is total means $t \downarrow$.

- A function $f : A \rightarrow B$ is total, iff $\forall a \in A. f(a) \downarrow$ (or, equivalently, $\text{dom}(f) = A$).

Remark:
Total partial functions are ordinary (non-partial) functions.
Remark:
Quantifiers always range over defined elements. So by $\exists m. f(n) \simeq m$ we mean: there exists a defined $m$ s.t. $f(n) \simeq m$.

So from $f(n) \simeq g(k)$ we cannot conclude $\exists m. f(n) \simeq m$ unless $g(k) \downarrow$. 
Remark 2.29

(a) If $a, b$ are constants, $s \simeq a, s \simeq b$, then $a = b$.

(b) For all terms we have $t \downarrow \iff \exists a. t \simeq a$.

(c) $f(t_1, \ldots, t_n) \downarrow \iff \exists a_1, \ldots, a_n. t_1 \simeq a_1 \land \cdots$

$$\land t_n \simeq a_n$$

$$\land f(a_1, \ldots, a_n) \downarrow .$$
Examples

- Assume $f : \mathbb{N} \sim \rightarrow \mathbb{N}$, $\text{dom}(f) = \{ n \in \mathbb{N} \mid n > 0 \}$. 
  $f(n) := n - 1$ for $n \in \text{dom}(f)$.

- Let $g : \mathbb{N} \sim \rightarrow \mathbb{N}$, $\text{dom}(g) = \{0, 1, 2\}$, $g(n) := n + 1$. 
  Then:
  
  $f(1) \downarrow$, $f(0) \uparrow$, $f(1) \simeq 0$, $f(0) \not\simeq n$ for all $n \in \mathbb{N}$.

  $g(f(0)) \uparrow$, since $f(0) \uparrow$.

  $g(f(1)) \downarrow$, since $f(1) \downarrow$, $f(1) \simeq 0$, $g(0) \downarrow$.

  $g(f(4)) \uparrow$, since $f(4) \downarrow$, $f(4) \simeq 3$, but $g(3) \uparrow$. 

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Examples

\[ f : \mathbb{N} \rightarrow \mathbb{N}, \text{dom}(f) = \{ n \in \mathbb{N} \mid n > 0 \}, \text{f}(n) := n - 1 \text{ for } n \in \text{dom}(f). \]

\[ g : \mathbb{N} \rightarrow \mathbb{N}, \text{dom}(g) = \{ 0, 1, 2 \}, g(n) := n + 1. \]

- \[ g(f(0)) \simeq f(0), \text{ since both expressions are undefined.} \]

- \[ g(f(1)) \simeq f(g(1)), \text{ since both sides are defined and equal to 1.} \]

- \[ g(f(0)) \not\simeq f(g(0)), \text{ since the left hand side is undefined, the right hand side is defined.} \]
Examples

\[ f : \mathbb{N} \rightarrow \mathbb{N}, \quad \text{dom}(f) = \{n \in \mathbb{N} \mid n > 0\}, \quad f(n) := n - 1 \quad \text{for} \quad n \in \text{dom}(f). \]

\[ g : \mathbb{N} \rightarrow \mathbb{N}, \quad \text{dom}(g) = \{0, 1, 2\}, \quad g(n) := n + 1. \]

\[ f(f(2)) \not\sim f(2), \quad \text{since both sides evaluate to different (defined) values.} \]
Examples

\[ f : \mathbb{N} \xrightarrow{\sim} \mathbb{N}, \text{dom}(f) = \{ n \in \mathbb{N} \mid n > 0 \} , \ f(n) := n - 1 \text{ for } n \in \text{dom}(f). \]

\[ g : \mathbb{N} \xrightarrow{\sim} \mathbb{N}, \text{dom}(g) = \{ 0, 1, 2 \} , \ g(n) := n + 1. \]

+, · etc. can be treated as partial functions. So for instance

\[ f(1) + f(2) \downarrow, \text{ since } f(1) \downarrow, f(2) \downarrow, \text{ and } + \text{ is total.} \]

\[ f(1) + f(2) \approx 1. \]

\[ f(0) + f(1) \uparrow, \text{ since } f(0) \uparrow. \]
Definition

Assume $f : \mathbb{N}^n \xrightarrow{\sim} \mathbb{N}$.

(a) The **range of** $f$, in short $\text{ran}(f)$ is defined as follows:

$$\text{ran}(f) := \{ y \in \mathbb{N} \mid \exists \vec{x}. (f(\vec{x}) \simeq y) \} \ .$$

(b) The **graph of** $f$ is the set $\text{G}_f$ defined as

$$\text{G}_f := \{ (\vec{x}, y) \in \mathbb{N}^{n+1} \mid f(\vec{x}) \simeq y \} \ .$$
Remark on $G_f$

- The notion “graph” used here has nothing to do with the notion of “graph” in graph theory.
- The graph of a function is essentially the graph we draw when visualising $f$. 
Remark on $G_f$

Example:

$$f : \mathbb{N} \sim \rightarrow \mathbb{N}, \quad f(x) = \begin{cases} \frac{x}{2}, & \text{if } x \text{ even}, \\ \bot, & \text{if } x \text{ is odd.} \end{cases}$$

We can draw $f$ as follows:
Remark on $G_f$

In this example we have

$$G_f = \{(0, 0), (2, 1), (4, 2), (6, 3), \ldots \}$$

These are exactly the coordinates of the crosses in the picture: