Lecture 1: Information Coding & Data Structures

Seminar ‘Foundations of Data Science’

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Overview of this Session

- Administrative Aspects
- Motivation for the Course
- Information Coding
- Data Structures

Administrative Aspects

Formalities

- MA-level Seminar “Foundations of Data Science for Social Scientists” (no. 615d539a)
  - Lecture Team:
    - Karsten Donnay (donnay@ipz.uzh.ch)
    - Marcel Blum (marcel.blum@uzh.ch)
  - Course dates: 14.06.2021 – 18.06.2021
    - Lecture: 10:15 – 12:00
    - Exercise: 14:00 – 15:45
  - Online teaching only:
    - Zoom: https://uzh.zoom.us/j/91462284423 (Password: 810882)
    - OLAT: https://lms.uzh.ch/url/RepositoryEntry/16964059152

Course Objectives

- Develop a good understanding of technical and conceptual foundations of data science approaches in the social sciences.
- Learn to apply them in relevant research settings while adhering to best practices and standards of data quality and reproducibility.
- Familiarize yourselves with relevant tools and approaches and learn to apply them to your own research questions.

Course Assessment

- Based on written exercises and assignments
  - Total of four shorter exercises with assignments
    - Given out during the exercises on Mon. through Thu.
    - Due the **next day** before the next exercise session, i.e., **before 14:00**
    - 5 points per assignment for a total of 20 points
  - Longer final project (coding and report)
    - Assigned on the last day of the class, i.e., Fri. Jun. 18
    - Due the **following week** on Fri. **Jun. 25 at 23:59**
    - 30 points for the final project
  - Final grade:
    - 40% (20 points) from exercises, 60% (30 points) from final project

Course Structure

– **Lectures:**
  Technical and theoretical background on key data science concepts and overview of practical applications in the social sciences.

– **Exercises & Assignments:**
  Practical walk-through of a data science pipeline to provide you with examples, hands-on experience and an overview of best practices.

– **Final Project:**
  Applying those skills in a data science application of your own choice including
  - Data collection/import and cleaning
  - Processing and analysis
  - Simple research application and presentation of results

Assignments – Details

- Typically three individual tasks
  - Made available through GitHub and on OLAT
  - Hand-in prior to deadline through “Drop Box” function on OLAT
  - Feedback and grading also through “Drop Box”

- Submission format
  - Should be solved directly in the Markdown file (please submit as .Rmd)
  - We encourage you to talk to your fellow students and **collaborate** but everyone has to submit their **own file as solution**, i.e., no straight copy-paste
  - Grading out of 5 points for each assignment (total of 20 points for all assignments)

Final Project – Details

- Idea:
  - Work on a topic you are interested in or that is related to your research/thesis
  - Identify a concrete **research question** you are trying to address
  - Apply the lessons-learned from this class in the context of this question
- Format:
  - Full data science pipeline from initial data collection/processing to data wrangling, extracting relevant information, analysis and presentation of results
  - Should also be done in Markdown and doubles as your project report; emphasis is on coding but we also expect
    - Motivation for your research question (& short overview of related research)
    - Text narrative that leads through al parts of the data science pipeline
    - Discussion of results and potential shortcomings

Access to Course Material

- OLAT: https://lms.uzh.ch/url/RepositoryEntry/16964059152
  - Main course resource for
    - Course syllabus & announcements
    - Lecture slides & recordings
    - Exercises & assignments
    - Solutions for assignments (after respective deadline)
- GitHub: https://github.com/css-zurich/fds-2021
  - Quick access to course materials
    - Lecture slides
    - Exercises & assignments
    - .Rmd files etc.

Course Outline

- Part 1: Foundations
  - *Day 1: Mon. 14.06.2021*
    - 10:15 – 12:00 Lecture 1: Information Coding & Data Structures (SWITCHcast)
    - 14:00 – 15:45 Exercise Session 1 (Zoom)
  - *Day 2: Tue. 15.06.2021*
    - 10:15 – 12:00 Lecture 2: Programming & Algorithms (SWITCHcast)
    - 14:00 – 15:45 Exercise Session 2 (Zoom)
  - *Day 3: Wed. 16.06.2021*
    - 10:15 – 12:00 Lecture 3: Complexity & Efficiency (SWITCHcast)
    - 14:00 – 15:45 Exercise Session 3 (Zoom)

Course Outline

- Part 2: Applications
  - *Day 4: Thu. 17.06.2021*
    - 10:15 – 12:00 Lecture 4: Data Collection & Quality (SWITCHcast)
    - 14:00 – 15:45 Exercise Session 4 (Zoom)
  - *Day 5: Fri. 18.06.2021*
    - 10:15 – 12:00 Lecture 5: Research on Digital Media (SWITCHcast)
    - 14:00 – 15:45 Exercise Session 5 (Zoom)

Motivation for the Course

Motivation for the Course

- We are in the middle of a data “revolution”
  - Wealth of new data that is becoming available
    - Very large
    - Frequently updated
    - Diverse sources
  - Computational methods critically important to handle and analyze these data
    - Automatization
    - Robustness
    - Reproducibility

Motivation for the Course

- BUT lack of fundamental understanding of the “tools” we use
  - Often only a working knowledge of high-level software programming
    - SPSS
    - STATA
    - R (but primarily only for statistics)
  - Complex research problems require more advanced skills
    - Automatize data retrieval and handling
    - Design efficient algorithms
    - Develop or adapt software that implements specific methods

Computational Social Science or Data Science?

- **Definition:** Computational Social Science (CSS)
  Computational social science refers to the academic sub-disciplines concerned with **computational approaches to the social sciences**. This means that computers are used to model, simulate, and analyze social phenomena.
- Computational Social Science vs. Data Science
  - Data science is typically more narrowly concerned with extracting knowledge from data:
    - Machine learning
    - Data mining
    - Statistics
    - Predictive analytics
  - We are in this class interested in data science applications in the social sciences, i.e., we really are landing more on the side of Computational Social Science…

Information Coding

Units of Information

- Smallest physical unit is 1 **bit**: 0 or 1
  - memory: a capacitor or a capacitor and several transistors
  - hard disk: magnetization
- Smallest logical unit is 1 **byte**: 8 bit
  - processor can usually only address entire bytes
  - i.e., coding 1 bit of information “wastes” 7 bits but typically individual pieces of information we store already require more than one bit to code

Units of Information

- Machine word:
  - fixed-sized piece of data handled as a unit by the instruction set or the hardware of a processor
  - depends on the width of the processor bus
    - 8 bit (1 byte) for 8088
    - 16 bit (2 byte) for 80286
    - 32 bit (4 byte) for 80686
    - 64 bit (8 byte) in most of today's processors
    - 128 bit (16 byte) for example in graphic cards
  - processor is fastest at processing whole machine words

Number Systems

- Unary Numeral Systems:
  - every natural number is represented by a sequence of symbols
  - to represent number N, an arbitrary symbol representing 1 is repeated N times
- Positional Notation:
  - composed of a finite number of numeric symbols
  - represent arbitrary numbers through positioning of those numeric symbols

Number Systems

- Examples:
  - Roman numerals:
    - hybrid notation: partially unary, but also positional notation
    - III = 3, MMXVI = 2016, MCMLXXXIII = 1983
  - Arabic numerals
    - positional notation
    - only 10 different numerical digits
    - includes a representation for 0

Arabic Numerals

- Positional notation with base β
- Base β is also often referred to as radix
  - radix 10: decimal notation (0 – 9)
  - radix 2: binary notation (0, 1)
  - radix 8: octal notation (0 – 7)
  - radix 16: hexadecimal notation (0 – 9, A – F)
- Notation convention is to indicate the base, if not clearly known, as subscript
  - $7_{10} = 7_8 = 111_2$
  - $9_{10} = 11_8 = 1001_2$
  - $14_{10} = 16_8 = 1110_2$

Examples

Decimal notation

- $5648_{10} = 5 \cdot 10^3 + 6 \cdot 10^2 + 4 \cdot 10^1 + 8 \cdot 10^0$

Binary notation

- $21_{10} = 1 \cdot 2^4 + 0 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 10101_2$

Octal notation

- $81_{10} = 1 \cdot 8^2 + 2 \cdot 8^1 + 0 \cdot 8^0 = 121_8$

Conversion Between Number Systems

– Conversion of octal to binary notation
  - every digit 0 – 7 can be represented exactly by 3 binary digits
  - allows for elegant and fast conversion digit by digit using blocks of 3 binary digits

Examples

- $123456_8 = 001\ 010\ 011\ 100\ 101\ 110_2$
- $4231_8 = 100\ 010\ 011\ 001_2$

Conversion Between Number Systems

– Conversion of hexadecimal to binary notation
  - every digit 0 – 9 and letters A – F can be represented by exactly 4 binary digits
  - allows for elegant and fast conversion digit by digit using blocks of 4 binary digits

Examples
- $23A7_{16} = 0010\ 0011\ 1010\ 0111_2$
- $B3D2_{16} = 1011\ 0011\ 1101\ 0010_2$

Hex	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Binary	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111

Negative Numbers

- Offset binary (or excess k) coding
  - move origin (0000) in the middle of the k digits
  - $z' = z - z^{k-1}$
  - fixed offset of all numbers, many values can not be used
  - simple binary arithmetic does not work any longer

decimal	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
unsigned	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111

decimal	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
excess k	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111

Negative Numbers

- Ones' Complement
  - leading bit codes the sign (0: +, 1: –)
  - $k-1$ digits to represent the absolute value of a given number
  - negation by inverting of the number
    - bit-wise flipping of 1s and 0s
  - two representations of 0:
    - 0000 0000
    - 1111 1111
  - addition requires "end-around carry"

Example

- $27_{10} = \underline{0}001\ 1011_2$
- $-27_{10} = \underline{1}110\ 0100_2$

Negative Numbers

- Two's Complement
  - leading bit codes the sign (0: +, 1: –)
  - negation by inverting of the number and adding 1
  - unique representation of 0: 0000 0000

Example

$27_{10} = 0001\ 1011_2$

$1110\ 0100_2$ (inverted)

$1110\ 0101_2 = -27_{10}$

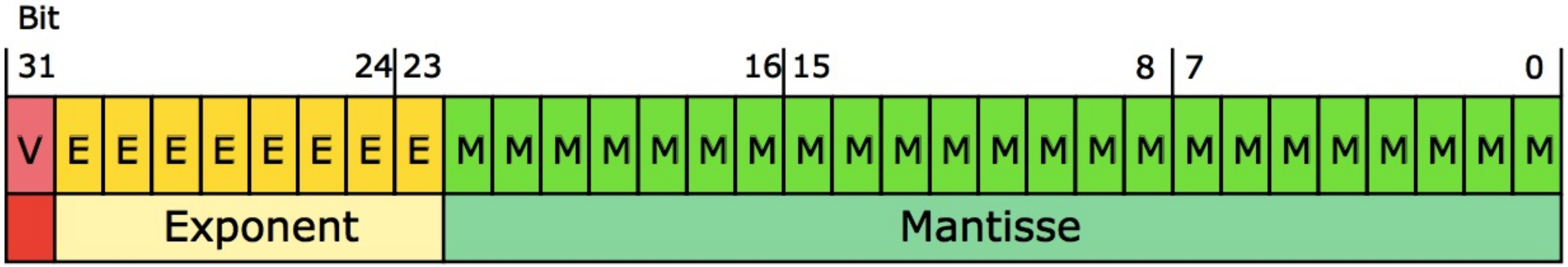
Real Numbers

- Fixed-point arithmetic
  - fixed assignment of k bits pre-decimal and decimal places
  - very inflexible
- Floating point
  - flexible division in sign (s), significand or mantissa (m) and exponent (e)
  - $z = s \cdot m \cdot \beta^e$

Real Numbers

- Floating point is standardized according to IEEE 754:
  - simple or double precision (32 or 64 bit)
  - 1 bit for the sign: $s = -1^S$
  - 23/52 bit significand with implicit 1: $m = 1.M$
    - leading 1 is not explicitly stored
    - significand and exponent are adjusted accordingly (normalized)
  - 8/11 bit exponent with bias: $\mathrm{e} = E - B$
    - bias permits sign less storage of negative exponents
    - $B = 127$ or $B = 1023$

IEEE 754



- Special representation for
  - 0: exponent and significand are both 0, i.e., there exists a positive and negative 0
  - ∞: exponent E only 1s, significand $M = 0$
- Value range:
  - simple precision (32 bit): $1.4 \cdot 10^{-45} \leq |z| \leq 3.4 \cdot 10^{38}$
  - double precision (64 bit): $4.9 \cdot 10^{-324} \leq |z| \leq 1.7 \cdot 10^{308}$

IEEE 754

Example

18.625 in single precision

- bias $B = 127 = 2^7 - 1$
- transform to binary notation:
  $18.625_{10} = 10010.101000\ldots_2$
- normalize:
  $10010.101000\ldots_2 = 1.0010101000\ldots \cdot 2^4$
- exponent $E = 4_{10} + 127_{10} = 131_{10} = 1000\ 0011_2$
- sign $S = 0$
- result:
  0|10000011|00101010000000000000000

Character Coding

– ASCII – Code: *American Standard Code for Information Interchange*
  - Standard since 1963, still in use today
  - initially 7 bit code for use in tele printers
    – 128 characters: 33 control characters, 95 printable characters

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL	BS	HT	LF	VT	FF	CR	SO	SI
1	DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
2		!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
6	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Character Coding

– Extension of ASCII-Codes to 8 bit (1 byte)
  - Code pages or character sets
    – CP850, CP437, IS0-8859-1 and ISO-8859-15 with special characters for Western Europe

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL	BS	HT	LF	VT	FF	CR	SO	SI
1	DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
2		!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
6	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL
8	PAD	HOP	BPH	NBH	IND	NEL	SSA	ESA	HTS	HTJ	VTS	PLD	PLU	RI	SS2	SS3
9	DCS	PU1	PU2	STS	CCH	MW	SPA	EPA	SOS	SGCI	SCI	CSI	ST	OSC	PM	APC
A	NBSP	¡	¢	£	€	¥	Š	§	š	©	ª	«	¬	SHY	®	¯
B	°	±	²	³	Ž	µ	¶	·	ž	¹	º	»	Œ	œ	Ÿ	¿
C	À	Á	Â	Ã	Ä	Å	Æ	Ç	È	É	Ê	Ë	Ì	Í	Î	Ï
D	Ð	Ñ	Ò	Ó	Ô	Õ	Ö	×	Ø	Ù	Ú	Û	Ü	Ý	Þ	ß
E	à	á	â	ã	ä	å	æ	ç	è	é	ê	ë	ì	í	î	ï
F	ð	ñ	ò	ó	ô	õ	ö	÷	ø	ù	ú	û	ü	ý	þ	ÿ

Character Coding

- Unicode
  - Addresses problems with ASCII and code pages
    - not all possible characters can be represented, e.g., kanji
    - meaning of a sign is dependent on code page
  - Development of standardized Unicode
    - simultaneous representation of all possible characters
    - fixed translation table
    - version 1.0 in 1991 with 65’536 different characters
    - current version 13.0 (as of March 2020) defines 143’859 of 1’114’112 possible characters

Unicode

- Division of full code space into 17 planes with 65 536 characters
  - specification using U+ and at least 4 hexadecimal numbers
  - one code correspond to exactly one character, e.g.: U+00DF = ß
- Plane 0, Basic Multilingual Plane (BMP)
  - currently used character sets, punctuation marks, control characters etc.
  - highly fragmented and mostly occupied
- Plane 1, Supplementary Multilingual Plane (SMP)
  - historical characters
  - domino and mahjong pieces
- Plane 2, Supplementary Ideographic Plane (SIP)
  - Chinese, Japanese and Korean characters

Representation of Unicode

- 3 bytes are necessary for all possible characters
  - not ideal for processing because it is not a machine word
  - “wasting” memory in many geographical regions, e.g. Europe
- Definition of Unicode Transformation Formats (UTF) as solution
  - UTF-16
    - 2 byte per characters, covers BMP
    - other areas are covered by combination of UTF-16 characters, still wastes memory
  - UTF-8
    - 1 byte per character, covers most important Western characters
    - additional characters can be covered by a combination of up to three UTF-8 characters
  - There also exists UTF-7 and UTF-32 but not as commonly used

Primitive Data Types

Type	Bits	Coding	Minimum	Maximum
boolean	1/8	truth value	false	true
byte	8	two's complement	-128	127
short	16	two's complement	-32 768	32 767
int	32	two's complement	-2 147 483 648	2 147 483 647
long	64	two's complement	-9 223 372 036 854 775 808	9 223 372 036 854 775 807
char	8-32	UTF-8 (standard)	0 (U+0000)	1 114 112 (U+0010FFFF)
float	32	IEEE 754	$\pm 1.4 \cdot 10^{-45}$	$\pm 3.4 \cdot 10^{38}$
double	64	IEEE 754	$\pm 4.9 \cdot 10^{-324}$	$\pm 1.7 \cdot 10^{308}$

Typing and Conversion

- R automatically types inputs
  - “Hello World” is automatically recognized as character string
  - 3.4 is automatically coded in floating point
    - R by default only has 64-bit double-precision
- Explicit type conversion is possible
  - Transform to numeric using as.numeric()
  - Transform to character using as.character()
    - Stores numbers as strings of characters
  - Transform to integer using as.integer()
    - Careful because simply “cuts of” decimal part

Strings

- Strings are immutable objects
  - Simply a sequence of individual characters
  - No standard “arithmetics” possible on strings
- R knows various methods for manipulation
  - Various “paste” commands to join strings
  - grep() (and similar commands) for pattern matching and replacement
    - Important together with regular expressions (RE) to match complex patterns in text
    - More on this in the second exercise, i.e., tomorrow afternoon
  - Important: “==” does **exact** string matching in R

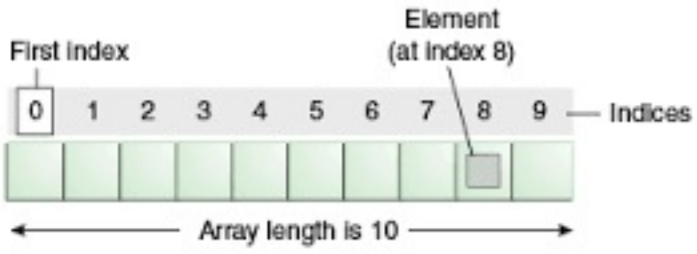
Data Structures

Data Structures

- **Definition:**
  Data structures are defined as data types together with operations defined on these data that enable and realize their access and management.
- We focus here on a few data structure with relevance for information storage
  - Data types typically vary by programming language
  - Primary data types used also depend on programming paradigm (more on this tomorrow)

Arrays

– **Definition:**
An array is a systematic arrangement of similar objects, usually in rows and columns.



- We address/access elements using the **index**
- In most programming languages indices from from 0 to n-1 for array of length n
- In R, we use indices from 1 to n
  - e.g.: a = c(5, 4, 3, 2, 1), a[2] = 4

Lists

- **Definition:**
  Lists are generic vectors containing other objects/data structures. This exact type of data structure is specific to R.

  - The idea is to use lists in R for collections of different types of data, i.e., collections of numeric and character values
    - Important: Arrays in R are typed, i.e., c(1, “2”, 3) converts all numeric to character
    - If you want this kind of “mixed” collections you have to use lists
  - Working with lists
    - [] gives you access to the whole list element
    - [[]] gives you access to the entries within that list element
    - list elements can have labels or no labels b = list(a = c(5, 4, 3, 2, 1)) or b = list(c(5, 4, 3, 2, 1))
      - If elements are labeled, you can access them with $, i.e., b$a, else with [] only

Data Frames

- **Definition:**
  Data frames is two dimensional data structure in R. It is a special case of a list which has each component of equal length, i.e., in other programming languages this is also often called a matrix or an nxm-array (i.e., n lines, m columns).

  - This data structure is the go-to solution for any kind of table structures in R, i.e., your usual spreadsheet data
  - It is relatively easy and fast to access and manipulate, also iteratively; you should be familiar with it already from your classes in statistics
  - Working with data frames
    - Accessing a given element requires specifying two indices, e.g. a[i,j] gives i-th row, j-th column of a
    - Accessing a whole row or column means leaving index j or i, respectively, empty
      - This is also often referred to as “slicing”

Other Data Structures

- There are many other important data structures, most of which have an implementation in R
  - All have specific applications in mind and are not suitable for every kind (or size) of data
  - Access and data manipulation might be feasible for some applications and not for others
  - In the following we take a look at one more important data structure that you will encounter quite often, the exercises touch upon a few others

Dictionaries

- **Definition:**
  Dictionaries are an abstract data type composed of a collection of (key, value) pairs, such that each possible key appears at most once in the collection.
  - Generalized keys (not just indices):
    - Characters, words, names etc.
  - Characteristics
    - Keys are not necessarily homogeneously distributed
      - Using an array spanning the whole range of values would waste memory
    - Use list of keys to index the dictionary
      - If no further conditions applied: sequential search
      - Worst case: have to search through ALL entries to find one

Dictionaries

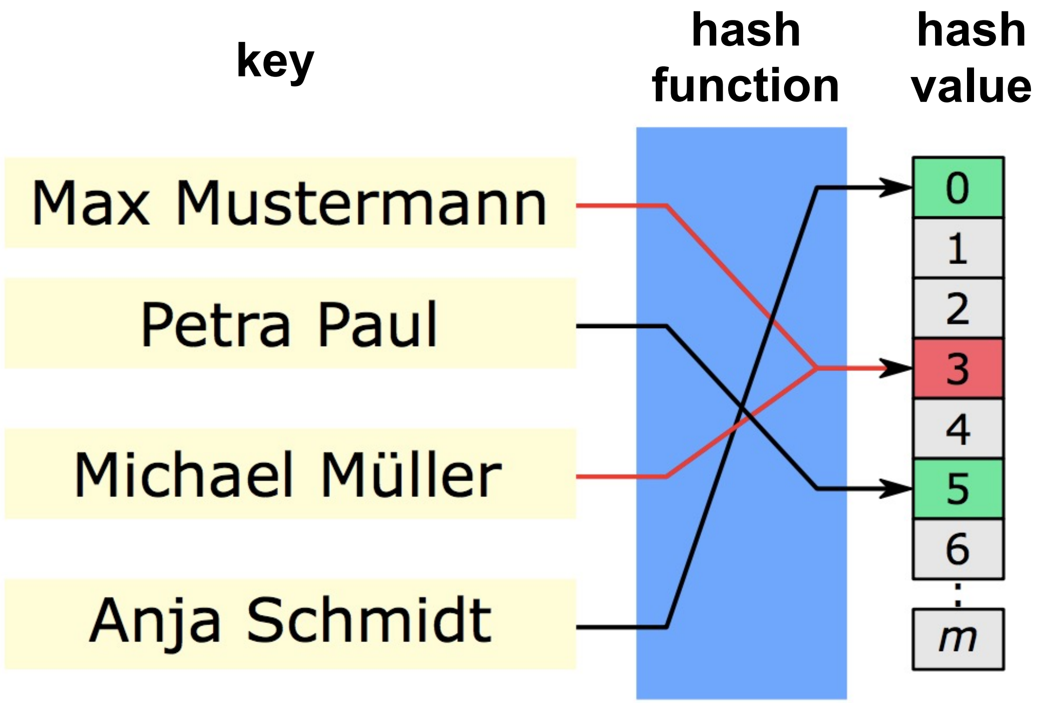
- Hash Tables (intuition)
  - Dictionaries typically use hash tables to effectively index sparse key values
  - Examples of hash tables
    - student ID numbers
      - 6-digit number, i.e. 10^6 possible values
      - BUT only of a few 10,000s are used at the same time
      - can map all numbers onto those slots
    - books in the library
      - book titles have maybe ≈50 characters that means $\sim 26^{50}$ possible titles
      - BUT a library has “only” millions of books

Dictionaries

- Hash Tables (formal)
  - Also referred to as associative arrays and used also in databases, cryptography etc.
  - **Definition: Hash function**
    A hash function $h: K \rightarrow \{0,1,\dots,m-1\}$ assigns to any given key k an index $0 \leq h(k) \leq m-1$.
    - Efficient mapping of indices but problem of so called **hash collisions**
      - Since we usually have $\mathrm{n} \gg m$ there is a very high likelihood that different keys get the same hash value
      - Requires special treatment that is dependent on how many hash values are already occupied

Hash Tables

– Example of hash collision



Hash Tables

- Hash function:
  - Central requirements
    - simple and fast to determine
    - balanced distribution to available indices to avoid collisions
    - fully deterministic calculation
    - (dynamically) adjustable to the number of free slots
  - Hash functions are usually based on natural numbers (with 0), i.e., $\mathrm{K} \subseteq N_0$
  - Usually direct calculation of the hash value of a given key (e.g., as a character string)

Hash Tables

- Examples for hash function:
  - Modulo operation
    - $\mathrm{h(k)} = k \; mod \; m$ gives value in range 0 to m-1 and balanced distribution
    - Best choice for avoiding hash collisions are prime numbers
  - Multiplicative hashing
    - Multiplication of an integer with an irrational number Θ and cutting of the integer part, then multiplication with m: $h(k) = \lfloor m(k \cdot \Theta - \lfloor k \cdot \Theta \rfloor) \rfloor$
    - Best results for the golden ratio $\phi^{-1} = \frac{\sqrt{5}-1}{2} \approx 0.6180339887 \ldots$

Up Next

- Exercise (this afternoon)
  - Data Science pipeline
  - Git & GitHub
  - First exercises in R with our working case
- Next lecture (tomorrow morning)
  - Programming
  - Algorithms