Leibniz Universität Hannover

Programmieren 1

Expressions

Human-Computer Interaction Group

Prof. Dr. Michael Rohs
michael.rohs@hci.uni-hannover.de

Lectures

#	Date	Topic	HÜ→	HÜ←
1	16.10.	Organization, computers, programming, algorithms, PostFix introduction (execution model, IDE, basic operators, booleans, naming)	1	22.10. 23:59
2	23.10.	PostFix (primitive types, functions, parameters, local variables, tests), recipe for atomic data	2	29.10. 23:59
3	30.10.	PostFix (operators, array operations, string operations), recipes for enumerations, intervals, and itemizations	3	5.11. 23:59
4	6.11.	Recipes for compound and variant data, iteration and recursion, PostFix (loops, association arrays, data definitions)	4	12.11. 23:59
5	13.11.	C introduction (if, variables, functions), Programming I C library	5	19.11. 23:59
6	20.11.	Data types, infix expressions, C language (enum, switch, while)	6	26.11. 23:59
7	27.11.	Compound and variant data, C language (formatted output, loops, struct, union)	7	3.12. 23:59
8	4.12.	C language (arrays, pointers) arrays: fixed-size collections, linear and binary search	8	10.12. 23:59
9	11.12.	Dynamic memory (malloc, free), recursion (recursive data, recursive algorithms)	9	17.12. 23:59
10	18.12.	Linked lists, binary trees, game trees, minimax algorithm	10	7.1. 23:59
11	8.1.	C language (program structure, scope, lifetime, linkage), function pointers, pointer lists	11	14.1. 23:59
12	15.1.	Objects, object lists, binary trees, search trees	12	21.1. 23:59
13	22.1.	Dynamic data structures (stacks, queues, maps, sets), iterators, documentation tools	(13)	
14	29.1.	This and that, C language (remaining C keywords)	(14)	

Review

- Execution model
  - C closer to hardware, typical CPUs: register machines
- Variables and constants: declaration, definition
  - Variables need to be declared (type) and defined (value)
- Conditional execution: if statement
  - if … else, dangling else
- Functions: declaration, definition
  - Function header declares signature, function body
- Programming I C library
- Atomic Data (in C)
- Loops: while, for, do-while

Preview

- Binary, octal, hexadecimal, decimal numbers `017, 0x1F`
- Data types and sizes `char, int, float, …`
- Operators, precedence, associativity `1+2*3`
- Type conversions `int i = (int)3.14;`
- Expressions, evaluation diagrams `x = ...;`
- Recipe for enumerations
- Recipe for intervals

PLACE-VALUE NOTATION (STELLENWERTSYSTEME)

Place-Value Notation

- Semantics of
  - 123
  - 321
- Place-value notation: Value of a symbol depends on its position
  - 123 = 1 * 100 + 2 * 10 + 3 * 1
  - 321 = 3 * 100 + 2 * 10 + 1 * 1
  - $12.34 = 1 * 10^1 + 2 * 10^0 + 3 * 10^{-1} + 4 * 10^{-2}$
- In general

$$\underbrace{h_m h_{m-1} \cdots h_0}_{\text{integer part}} \underbrace{.}_{\text{radix point}} \underbrace{h_{-1} \cdots h_{-n}}_{\text{fractional part}} = \sum_{i=-n}^{m} h_i \cdot \underbrace{10}_{\text{does it have to be 10?}}{}^{i} \quad m,n \in N \quad h_i \in \{0,1,\ldots,9\}$$

Place–Value Notation: Decimal and Binary

- Place-value notation: Value of a symbol depends on its position

$$h_m h_{m-1} \cdots h_0 . h_{-1} \cdots h_{-n} = \sum_{i=-n}^{m} h_i \cdot b^i \quad m,n,b \in N \quad h_i \in \{0,1,\ldots,b-1\}$$

- Decimal system
  - Base b=10 (decimal)
  - Digit at position i is multiplied by 10^i
  - **Example:** 123.45_{10} means $1*10^2 + 2*10^1 + 3*10^0 + 4*10^{-1} + 5*10^{-2}$
- Binary system
  - Base b=2 (binary, dual)
  - Digit at position i is multiplied by 2^i
  - **Example:** 101.101_2 means $1*2^2 + 0*2^1 + 1*2^0 + 1*2^{-1} + 0*2^{-2} + 1*2^{-3}$

Binary System

Developed by Gottfried Wilhelm Leibniz (article “Explication de l’Arithmétique Binaire”, 1703)

- 1646 born in Leipzig
- 1672/73 completed work on computing machine
  - Add / subtract / multiply / divide
  - Difficult to build at the time
- 1676 became Hofrat and Hofbibliothekar in Hannover
- 1703 published work on binary system
  - Basis for modern computer systems
- 1716 died in Hannover

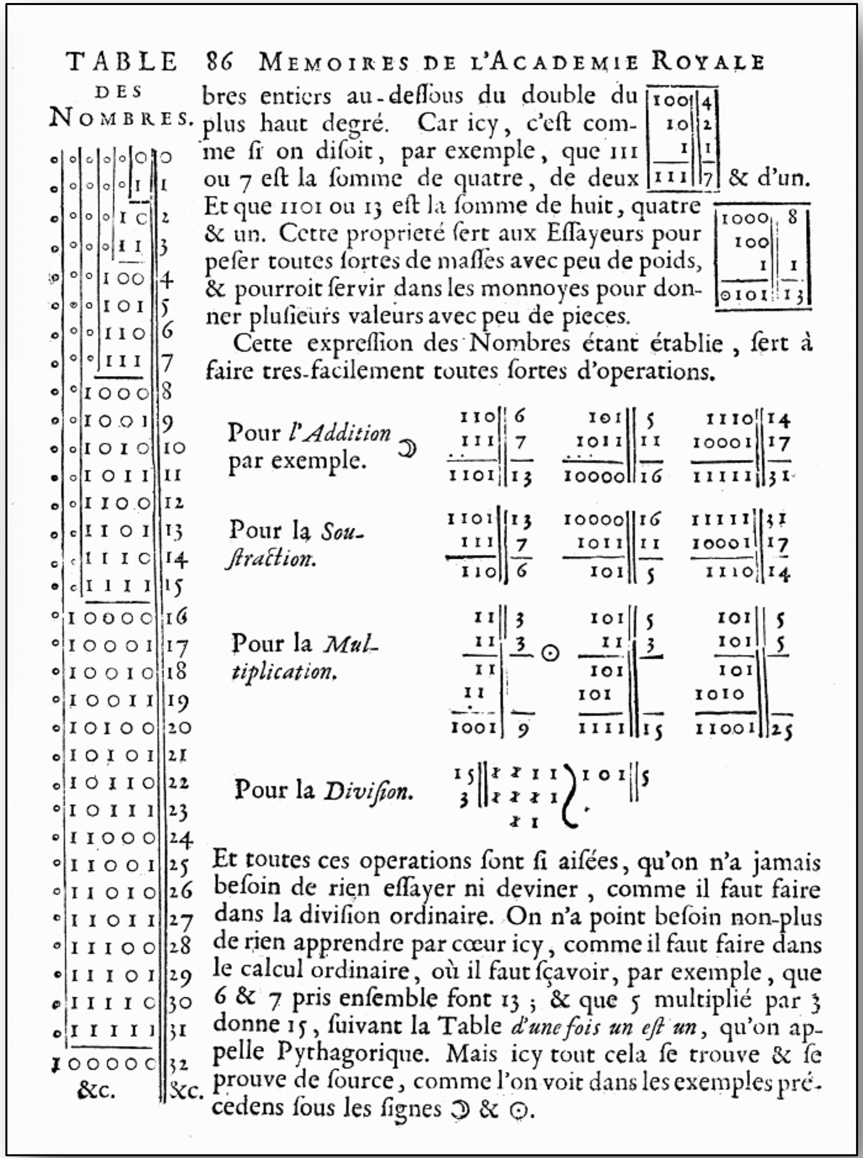


TABLE DES NOMBRES.

0 0 0 0 0 0	0
0 0 0 0 0 1	1
0 0 0 0 1 0	2
0 0 0 0 1 1	3
0 0 0 1 0 0	4
0 0 0 1 0 1	5
0 0 0 1 1 0	6
0 0 0 1 1 1	7
0 0 1 0 0 0	8
0 0 1 0 0 1	9
0 0 1 0 1 0	10
0 0 1 0 1 1	11
0 0 1 1 0 0	12
0 0 1 1 0 1	13
0 0 1 1 1 0	14
0 0 1 1 1 1	15
0 1 0 0 0 0	16
0 1 0 0 0 1	17
0 1 0 0 1 0	18
0 1 0 0 1 1	19
0 1 0 1 0 0	20
0 1 0 1 0 1	21
0 1 0 1 1 0	22
0 1 0 1 1 1	23
0 1 1 0 0 0	24
0 1 1 0 0 1	25
0 1 1 0 1 0	26
0 1 1 0 1 1	27
0 1 1 1 0 0	28
0 1 1 1 0 1	29
0 1 1 1 1 0	30
0 1 1 1 1 1	31
1 0 0 0 0 0	32
&c.	&c.

86 MEMOIRES DE L’ACADEMIE ROYALE

bres entiers au-deſſous du double du plus haut degré. Car icy, c’eſt comme ſi on diſoit, par exemple, que 111 ou 7 eſt la ſomme de quatre, de deux & d’un. Et que 1101 ou 13 eſt la ſomme de huit, quatre & un. Cette proprieté ſert aux Eſſayeurs pour peſer toutes ſortes de maſſes avec peu de poids, & pourroit ſervir dans les monnoyes pour donner pluſieurs valeurs avec peu de pieces.

100	4
10	2
1	1
111	7

1000	8
100	4
1	1
1101	13

Cette expreſſion des Nombres étant établie, ſert à faire tres-facilement toutes ſortes d’operations.

Pour l’*Addition* par exemple. ☽

110	6	101	5	1110	14
111	7	1011	11	10001	17
1101	13	10000	16	11111	31

Pour la *Souſtraction.*

1101	13	10000	16	11111	31
111	7	1011	11	10001	17
110	6	101	5	1110	14

Pour la *Multiplication.* ⊙

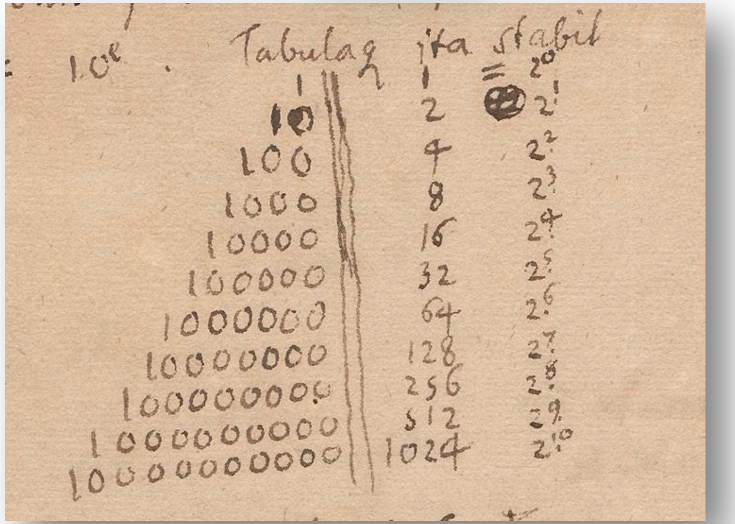
11	3	101	5	101	5
11	3	11	3	101	5
11		101		101	
11		101		1010	
1001	9	1111	15	11001	25

Pour la *Diviſion.* 15 / 3 | 1111 / 111 / 11 | 101 | 5

Et toutes ces operations ſont ſi aiſées, qu’on n’a jamais beſoin de rien eſſayer ni deviner, comme il faut faire dans la diviſion ordinaire. On n’a point beſoin non-plus de rien apprendre par cœur icy, comme il faut faire dans le calcul ordinaire, où il faut ſçavoir, par exemple, que 6 & 7 pris enſemble font 13; & que 5 multiplié par 3 donne 15, ſuivant la Table *d’une fois un eſt un*, qu’on appelle Pythagorique. Mais icy tout cela ſe trouve & ſe prouve de ſource, comme l’on voit dans les exemples précedens ſous les ſignes ☽ & ⊙.

Powers of 2

2^x	binary	decimal
2^{10}	10000000000	1024
2^{9}	1000000000	512
2^{8}	100000000	256
2^{7}	10000000	128
2^{6}	1000000	64
2^{5}	100000	32
2^{4}	10000	16
2^{3}	1000	8
2^{2}	100	4
2^{1}	10	2
2^{0}	1	1
2^{-1}	0.1	0.5
2^{-2}	0.01	0.25
2^{-3}	0.001	0.125



Leibniz: „Alles aus dem Nichts zu entwickeln genügt Eins (Omnibus ex nihilo ducendis sufficit unum)."

Place-Value Notation: Octal and Hexadecimal

- Octal system
  - Base b=8 (octal)
  - 8 symbols: 0, 1, 2, 3, 4, 5, 6, 7
  - Digit at position i is multiplied by 8^i
  - **Example:** 76.54_8 means $7*8^1 + 6*8^0 + 5*8^{-1} + 4*8^{-2}$

- Hexacimal system
  - Base b=16 (hexadecimal, sedezimal)
  - 16 symbols: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
  - Digit at position i is multiplied by 16^i
  - **Example:** $A9.F8_{16}$ means $10*16^1 + 9*16^0 + 15*16^{-1} + 8*16^{-2}$

Powers of 16

16^x	hexadecimal	decimal
16^8	100000000	4294967296
16^7	10000000	268435456
16^6	1000000	16777216
16^5	100000	1048576
16^4	10000	65536
16^3	1000	4096
16^2	100	256
16^1	10	16
16^0	1	1
16^{-1}	0.1	0.0625
16^{-2}	0.01	0.00390625

Counting in Binary

decimal	binary	comment
0	0	need 1st position
1	1	
2	10	need 2nd position
3	11	
4	100	need 3rd position
5	101	
6	110	
7	111	
8	1000	need 4th position
9	1001	
10	1010	
11	1011	
12	1100	
13	1101	
14	1110	
15	1111	

assume we have only 4 bits available,
what happens if we increment 1111?

Positive and Negative Numbers: Two's Complement

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

- First bit is a "sign bit"
  - first bit 0: number is positive or zero
  - first bit 1: number is negative
- To flip the sign (+x to –x)
  - invert bit pattern, add 1
- Examples
  - 0000_2 $(=0_{10})$ → 1111_2 → 0000_2 $(=0_{10})$
  - 0001_2 $(=1_{10})$ → 1110_2 → 1111_2 $(=-1_{10})$
  - 1110_2 $(=-2_{10})$ → 0001_2 → 0010_2 $(=2_{10})$

assume we have only 4 bits available, what happens if we increment 0111?

Computing with Binary Numbers

- Representing numbers is not enough, we want compute with them
- Basic arithmetic works fine with binary representations
- Addition: Subtraction:

Addition	Example
$0+0=\ 0$	1011_2
$0+1=\ 1$	$+0011_2$
$1+0=\ 1$	1 1
$1+1=10_2$	1110_2

Subtraction	Example
$0-0=\ 0$	0100_2
$0-1=-1$	-0110_2
$1-0=\ 1$	1 1
$1-1=\ 0$	1110_2

or...

Subtraction	Example
add two's complement $x-y = x+(-y)$	0100_2-0110_2 $= 0100_2+1010_2$ $= 1110_2= -2$

Arithmetic Overflow Experiment

- What is the output of this program? Why?

```
#include "base.h"
int main(void) {
    signed char c = 0x7f; // 7F16 = 710 * 161 + 1510 * 160 = 011111112 = 12710
    printiln(c);
    c = c + 1;
    printiln(c);
    c = 127;
    printiln(c);
    c = c + c;
    printiln(c);
    return 0;
}
```

$7F_{16} = 7_{10} * 16^1 + 15_{10} * 16^0 = 01111111_2 = 127_{10}$

Output?	
Output?	127
Output?	-128
Output?	127
Output?	-2

```
       ...
1111 1110 = -2
1111 1111 = -1
0000 0000 =  0
0000 0001 =  1
0000 0010 =  2
       ...
```

```
  0111 1111
+ 0111 1111
= 1111 1110
```

Converting between Binary Octal, Hexadecimal and Decimal

- Binary to Octal and Hexadecimal

octal	0			5			7			2		
binary	0	0	0	1	0	1	1	1	1	0	1	0
hexadecimal	1				7				A			

$$
\begin{aligned}
&5*8^2+7*8^1+2*8^0 \\
=\ &2^8+2^6+2^5+2^4+2^3+2^1 \\
=\ &1*16^2+7*16^1+10*16^0 \\
=\ &378
\end{aligned}
$$

- to Decimal

$$h_m h_{m-1} \cdots h_0 . h_{-1} \cdots h_{-n} = \sum_{i=-n}^{m} h_i \cdot b^i \quad m,n,b \in N \quad h_i \in \{0,1,\ldots,b-1\}$$

- Decimal to Binary
  - while (d != 0) { if (d even) print('0') else print('1'); d = d / 2; }
  - Example: d=11_{10}: 11, 5, 2, 1

    prints: 1 1 0 1 → (reverse)→ 1011_2

DATA TYPES AND SIZES

Interpreting Bit Patterns as Values

- Computers only store bit patterns
  - ... but we are not interested in bit patterns (typically)
  - we are interested in data, representing real-world information
- Need to interpret bit patterns
  - as characters
  - as integers
  - as floating-point numbers
- Limited capacity for each variable
  - cannot represent all integers $\mathbb{Z}$
  - cannot represent all real numbers $\mathbb{R}$

How many different values can be stored in an 8-bit variable?

How many different values can be stored in an n-bit variable?

Data Types

- Data types
  - Specify what kind of value a variable stores
  - Give meaning to bit patterns
  - C allows access to raw bit pattern, most other languages don't
  - Allows re-interpretation of bit pattern, flexible but error-prone
- Set of possible values and operations on these values
  - Operators are specific to data types
  - Example: Integer division is different from floating-point division
- Example
  - Bit pattern in memory cell: 01110000
  - For data type char, interpreted as ASCII character 'p'
  - For data type integer, interpreted as $1*2^6 + 1*2^5 + 1*2^4 = 112$

Built-in Data Types in C

- Basic types
  - char single byte, holds a single ASCII character
  - int integer number
  - float single precision floating-point number
  - double double precision floating-point number
  - bool Boolean type (values: true, false)
- Qualifiers
  - short, long modify the number of bits used
  - signed, unsigned if omitted then signed is assumed
- Example combinations
  - short int (= short)
  - unsigned long int (= unsigned long)
  - signed int (= int)

Typical Sizes of Built-in Data Types

- C size rules (number of bits in memory)
  - char < short ≤ int ≤ long
  - 8 bits ≤ char, 16 bits ≤ short, 16 bits ≤ int, 32 bits ≤ long
- Actual size depends on hardware (see <limits.h>, <float.h>)
- Typical integer sizes and ranges

char	8 bits	$-2^{7}..2^{7}-1$	-128..127
unsigned char	8 bits	$0..2^{8}-1$	0..255
short	16 bits	$-2^{15}..2^{15}-1$	-32768..32767
unsigned short	16 bits	$0..2^{16}-1$	0..65535
int	32 bits	$-2^{31}..2^{31}-1$	-2147483648..2147483647
unsigned int	32 bits	$0..2^{32}-1$	0..4294967295
long	64 bits	$-2^{63}..2^{63}-1$	
unsigned long	64 bits	$0..2^{64}-1$	

Typical Sizes of Built-in Data Types

- Floating point sizes and ranges
  - float 32 bits 6 significant decimal digits, $10^{-38}..10^{38}$
  - double 64 bits 15 significant decimal digits, $10^{-307}..10^{308}$
  - long double 128 bits 18 significant decimal digits, $10^{-4931}..10^{4932}$

Data Type Sizes Experiment

- sizeof operator yields the number of bytes of its operand
- Examples (for gcc and macOS 10.15):

`println(sizeof(char));`	1 byte
`println(sizeof(short int));`	2 bytes
`println(sizeof(int));`	4 bytes
`println(sizeof(long int));`	8 bytes
`println(sizeof(bool));`	1 byte
`println(sizeof(float));`	4 bytes
`println(sizeof(double));`	8 bytes
`println(sizeof(long double));`	16 bytes

DATA TYPES AND SIZES: FLOATING-POINT NUMBERS

Floating-Point Numbers (Float and Double)

- Float:
  - 32 bits

1	8 bits	23 bits
S	E	M

- Double:
  - 64 bits

1	11 bits	52 bits
S	E	M

- IEEE Standard for Floating-Point Arithmetic (IEEE 754) defines
  - Arithmetic operations
  - Rounding rules
  - Exceptions (division by zero, overflow)
  - Special values ("not a number" NaN, +∞, -∞)

Institute of Electrical and Electronics Engineers, "i-triple-e"

Floating-Point Numbers (float, 32 bits)

- Encode floating-point number x as a bit pattern (of 32 bits)
- Float:
  - 32 bits

1	8 bits	23 bits
S	E	M

encoded in 32 bits: sign, integer, shift

- Encode $x = s * m * 2^e$ as a bit pattern [S, E, M]:
  - S = 0 for positive numbers, S = 1 for negative numbers
  - $M = 2^{23} * (m - 1)$, with $1 \leq m < 2$
  - $E = e + 127$
  - Example: $-0.5 = -2^{-1} = -1 * 1 * 2^{-1}$ ➔ S = 1, M = 0, E = 126
- Decode bit pattern [S, E, M]:
  - Define $s = (-1)^S$
  - $m = 1 + M / 2^{23}$
  - $e = E - 127$

$2^{-23} = 1.192 \times 10^{-7}$

Floating-Point Numbers (float, 32 bits)

- Encode floating-point number x as a bit pattern (of 32 bits)
- Write as $x = s * m * 2^e$
  - Sign: $s \in \{-1, 1\}$
  - Mantissa: $1 \leq m < 2$ (German: Mantisse)
  - Exponent: $-127 \leq e < 128$ (how to shift ("float") the point)
  - Example: $x = -0.5 = \underbrace{-1}_{s} * \underbrace{1}_{m} * \underbrace{2^{-1}}_{2^e}$
- Encodable values when floating the point from -2 to 2
  - $e = -2 \Rightarrow x = m * 2^{-2} \Rightarrow 0.25 \leq x < 0.50$
  - $e = -1 \Rightarrow x = m * 2^{-1} \Rightarrow 0.50 \leq x < 1.00$
  - $e = 0 \Rightarrow x = m * 2^{0} \Rightarrow 1.00 \leq x < 2.00$
  - $e = 1 \Rightarrow x = m * 2^{1} \Rightarrow 2.00 \leq x < 4.00$
  - $e = 2 \Rightarrow x = m * 2^{2} \Rightarrow 4.00 \leq x < 8.00$

Floating-Point Precision Experiment

- What is the output of this program? Why?

```
#include "base.h"
int main(void) {
    float f = 2e10f + 1;
    printdln(f - 2e10f);        Output?  0.0
    double d = 2e10 + 1;
    printdln(d - 2e10);         Output?  1.0
    return 0;
}
```

20000000000.0 encoded as:

S	E	M
0	161	1377017

20000000001.0 encoded as:

S	E	M
0	161	1377017

S	E	M
0	161	1377018

decodes to 20000002048.0

OPERATORS

Operators in C

<table>
<tr><th></th><th>Operators</th></tr>
<tr><td>function call</td><td>( )</td></tr>
<tr><td>array access</td><td>[ ]</td></tr>
<tr><td>member access</td><td>-> .</td></tr>
<tr><td>(de-)referencing</td><td>* (indirection) & (address of)</td></tr>
<tr><td>arithmetic</td><td>+ - * / %(mod.) ++(incr.) --(decr.) +/-(unary)</td></tr>
<tr><td>relational</td><td>< <= > >=</td></tr>
<tr><td>equality</td><td>== (equals) != (not equals)</td></tr>
<tr><td>logical</td><td>&& (and) || (or) ! (not)</td></tr>
<tr><td>bitwise</td><td>& (and) | (or) ^ (exclusive or) ~ (flip bits)</td></tr>
<tr><td>bit shift</td><td><< >></td></tr>
<tr><td>type cast</td><td>(type)</td></tr>
<tr><td>sizeof</td><td>sizeof(type)</td></tr>
<tr><td>conditional expression</td><td>test ? a : b</td></tr>
<tr><td>assignment operators</td><td>= += -= *= /= %= &= ^= |= <<= >>=</td></tr>
<tr><td>comma</td><td>,</td></tr>
</table>

Operators and Expressions

- Operators
  - Combine operands to a new value
  - Unary operators take one operand
    - Example: -5 (unary integer minus operator)
  - Binary operators take two operands
    - Example: 1 + 2 (binary integer plus operator)
- Expressions
  - Example: (1 + 2) * 3 + f(7)
  - Consist of operands and operators, including function calls
  - Are evaluated to a new value

Arithmetic, Relational, and Equality Operators

- Binary arithmetic operators: +, -, *, /, %
  - / integer division truncates the fractional part
  - % is the modulo operator (rest of integer division)

3 / 2 is 1 (not 1.5)

- Relational operators
  - > >= < <=
  - yield 1 if true, 0 otherwise

no **boolean** type in traditional C: integer 0 represents false, all other integers represent true

- Equality operators
  - == !=
  - yield 1 if true, 0 otherwise

no built-in boolean type in traditional C

Increment and Decrement Operators

- ++ --
- prefix (++n): changes variable before value is used
- postfix (n++): changes variable after value has been used
- Example:

```
int n, x;
n = 5;
x = n++; // assigns value of n to x, then increments n
// assertion: x == 5, n == 6
n = 5;
x = ++n; // increments n, then assigns (incremented) value of n to x
// assertion: x == 6, n == 6
```

Logical Operators

- Logical operators
  - && (and) || (or)
  - 0 means false, not-0 means true
  - yield 1 if true, 0 otherwise

a	b	a && b	a || b
false	false	false	false
false	true	false	true
true	false	false	true
true	true	true	true

- Expressions connected by logical operators
  - Evaluation is left to right and stops as soon as truth value is known
    - Short-circuit evaluation
  - Example: if (a == 1 || b == 2 || c == 3)...
    evaluation stops after first equality operator if a == 1
- Unary negation operator (“not”)
  - !   converts non-zero operand to 0, converts 0 operand to 1
  - Example: if (!valid)... means “if not valid...”

Bitwise Operators

- & bitwise AND
  - example: 0101_2
    $\& \; 0110_2$
    $= 0100_2$
- | bitwise inclusive OR
  - example: 0101_2
    $| \; 0110_2$
    $= 0111_2$
- ^ bitwise exclusive OR
  - example: 0101_2 ^ $0110_2 = 0011_2$
- ~ not (flip bits, one's complement)
  - example $\sim 0101_2 = 1010_2$

a	b	a & b	a | b	a ^ b
0	0	0	0	0
0	1	0	1	1
1	0	0	1	1
1	1	1	1	0

Bit Shift Operators

- << left shift
  - x << n shifts x left by n bit positions
  - fills with 0s
  - Example: $1010_2 << 2 = 101000_2$
- >> right shift
  - x >> n shifts x right by n bit positions
  - fills with 0s for unsigned quantities
  - Example: $1110_2 >> 2 = 11_2$
  - fills with sign bit or 0s depending on machine behavior for signed quantities

Assignment Operators

- Assignment operators and expressions
  - $expr_1$ **op**= $expr_2$ is equivalent to $expr_1$ = ($expr_1$) **op** ($expr_2$)
  - where **op** is one of + - * / % << >> & ^ |

- Examples
  - x *= 3; means x = x * 3;
  - x -= 5; means x = x – 5;
  - x *= 3 + y; means x = x * (3 + y);

- Assignment operators have a type and a value
  - type is that of $expr_1$
  - value is that after the assignment

Conditional Expression

- Conditional expression
  - $expr_1$? $expr_2$: $expr_3$
  - if $expr_1$ is true, evaluate $expr_2$ otherwise evaluate $expr_3$
  - Example: z = (a > b) ? a : b;   // z = max(a,b)

- Sometimes useful replacement for
  if (expr) … else …

Evaluation Order

- C does not specify the order in which operands of an operator are evaluated
  - Example: x = f() + g()
  - f may be called before g…
  - … or g may be called before f

Type Conversions

- Operands of different types are converted to a common type
- Rules for binary operators with signed operands
  - if either is long double, convert other to long double
  - else if either is double, convert other to double
  - else if either is float, convert other to float
  - else convert char and short to int
  - then, if either is long, convert other to long
- Examples
  - double d; float f; char c; int i; long l;
  - d * f // convert f to double, double-multiplication
  - i * f // convert i to float, float-multiplication
  - c * i // convert c to int, int-multiplication

Type Conversion Examples

Type conversions when evaluating expressions

double d; float f; char c; int i; long l;

```
  c   *   i  + d
char * int + double
 int * int + double
    int    + double
 double    + double
       double
```

```
(c      -   '0'  ) * 3.14
(char   -  char)   * double
( int   -   int  ) * double
    int            * double
  double           * double
          double
```

Type Conversions in Assignments and for Arguments

- Conversion rules also apply across assignments
  - `int i; char c;`
  - `i = c; // sign extension depends on whether char on machine is signed`
  - `c = i; // high-order bits are dropped`

- … and when passing arguments to functions
  - `double sqrt(double x);  // method declaration`
  - `int i = 5;`
  - `int j = sqrt(i);               // convert i to double`

Type Cast Operator

- Explicit type conversions
  - (type name) expression

- Example:
  double d = 123.456;
  int i = (int)(d+0.5);   // rounding for positive numbers

- Example:
  int i = 5;
  int j = 123;
  double d;
  d = i / j;   // integer division, d == 0
  d = (double) i / j;   // force floating-point division, d == 0.04065...

Type Cast Operator

- Casting to a smaller type means that
  the set of representable values becomes smaller
  - Values might get truncated
- Example:

```
short s = 0x1234;     // 16 bits
char c = 0;           // 8 bits
println(s);           // prints 4660 = 0x1234
c = s;
println(c);           // prints 52 = 0x34
```

EXPRESSIONS

Operator Precedence (Kernighan, Ritchie, Table 2-1)

	Operators
highest	( ) [ ] -> .
	! ~ ++ -- +-(unary) *(indirection) &(address of) (type) sizeof
	* / %
	+ -
	<< >>
	< <= > >=
	== !=
	&
	^
	|
	&&
	||
	?:
	= += -= *= /= %= &= ^= |= <<= >>=
lowest	,

expressions are evaluated in order of operator precedence and associativity

use parentheses (...) if in doubt

Precedence and Associativity

- **Precedence** defines order of evaluation of different operators
  - 1 + 2 * 3 means 1 + (2 * 3),   * has higher precedence than +
  - value of expression is 7
- **Associativity** defines order of evaluation
  of operators of the same precedence
  - 1 - 2 + 3 means (1 – 2) + 3,   + and - are left-to-right associative
  - value of expression is 2
- Evaluation diagrams (Auswertungsdiagramme) show order of evaluation

```
1 + 2 * 3        1 - 2 + 3
    -----        -----
1 +   6           -1   + 3
-------          ---------
   7                 2
```

sometimes multiple valid orders

Integer Division

- Integer division first, then integer multiplication:

  $$\underline{5 / 3} * 2$$
  $$\underline{1 \quad * 2}$$
  $$2$$

- Integer multiplication first, then integer division:

  $$\underline{5 * 2} / 3$$
  $$\underline{10 \; / 3}$$
  $$3$$

- Typically integer division last in an expression

Assignments (are expressions as well)

- In C, an assignment is an expression and has a value
- Left-hand side of an assignment must be a variable (an "Lvalue")
- Assignment is right-to-left associative

$$a = b = \underline{c = 0}$$
$$a = \underline{b = \quad 0}$$
$$\underline{a = \quad 0}$$
$$0$$

- Using assignments in conditions:
  - if ((i = i_input()) != 0) …
- Can easily get unreadable:
  - a = 3 * (b = (c = 5) + 1);
  - better: c = 5; b = c + 1; a = 3 * b;

Assignments (are expressions as well)

- With parentheses:
  if ((i = i_input()) != 0) ...
  (i = 5) != 0 5 → i
  5 != 0
  1

- Without parentheses:
  if (i = i_input() != 0) ...
  i = 5 != 0
  i = 1 1 → i
  1

	Operators
highest	( ) [ ] -> .
	! ~ ++ -- +-(unary) *(indirection)
	* / %
	+ -
	<< >>
	< <= > >=
	== !=
	&
	^
	|
	&&
	||
	?:
	= += -= *= /= %= &= ^= |=
lowest	,

Evaluating Complicated Expressions

- In C, this is a valid expression
  - 4 < 8 && 21 + 3 != 10
  - What is the result?
- C treats boolean values as integers
  - logical operators yield 0 or 1

4 < 8 && 21 + 3 != 10

4 < 8 && 24 != 10

1 && 24 != 10

1 && 1

1

- Recommendations
  - For readability add parentheses to make the order of evaluation explicit (...)
  - Simplify expressions
  - Use multiple simpler expressions

	Operators
highest	( ) [ ] -> .
	! ~ ++ -- +-(unary) *(value of) &(address of) (type) sizeof
	* / %
	+ -
	<< >>
	< <= > >=
	== **!=**
	&
	^
	|
	&&
	||
	?:
	= += -= *= /= %= &= ^= |= <<= >>=
lowest	,

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RECIPE FOR ENUMERATIONS

Enumerations

- An enumeration type can represent one of a fixed number of distinct values
- Each enumerated value names a category and does not carry any additional data
- Example
  - Suit of cards (diamonds ♦, clubs ♣, hearts ♥, and spades ♠)
  - Continents (Europe, Asia, Africa, etc.)
- In C, enumerations are written as enum

enum

- Enumeration constants
  - enum Continent { EUROPE, ASIA }; // EUROPE == 0, ASIA == 1
  - enum Months { JAN = 1, APR = 4, JUL = 7, OCT = 10 };
- Enums behave like integers
  - Internally, C represents enumeration names as integer constants
  - First name gets value 0, second name gets value 1, etc.
  - Explicit assignment of constant values possible (see above)

1. Problem Statement

- Write down the problem statement as a comment.
  - What is the relevant information?
  - What should the function do with the data?

- Example

```
/*
Design a function that returns the next color of a traffic light
given the current color of the traffic light.
*/
```

2. Data Definition

- How should domain information be represented as data in the program? How to interpret the data as real-world information?

- Data definition

```
enum TrafficLight {
    RED,
    RED_YELLOW,
    GREEN,
    YELLOW
};
```

3. Function Signature

- Function signature as a comment
  - Parameter types left of the arrow (comma separated)
  - Result type right of the arrow

- Example

  ```
  // enum TrafficLight -> enum TrafficLight
  ```

4. Function Name

- Preliminary function name
  - Short, non-abbreviated, descriptive name that describes what the function does

- Example

  traffic_light_next

5. Function Header

- Add function signature to name
- Preliminary parameter names
  - Short, non-abbreviated, descriptive name that describes what the parameter means
- Example

```
enum TrafficLight traffic_light_next(enum TrafficLight tl);
```

6. Function Stub

- Function stub returns an arbitrary value from the function's range
- The function stub compiles

- Example

```
enum TrafficLight traffic_light_next(enum TrafficLight tl) {
    return RED;
}
```

7. Purpose Statement

- Briefly describes what the function does. Ideally as a single sentence.

- Example

  ```
  // Produces the next color of a traffic light
  // given the current color of the traffic light.
  ```

8. Examples and Expected Results

- Examples
  - If the traffic light is RED, expect RED_YELLOW as the next state.
  - If the traffic light is RED_YELLOW, expect GREEN as the next state.
  - If the traffic light is GREEN, expect YELLOW as the next state.
  - If the traffic light is YELLOW, expect RED as the next state.
- Test function

```
void traffic_light_next_test() {
    test_equal_i(traffic_light_next(RED), RED_YELLOW);
    test_equal_i(traffic_light_next(RED_YELLOW), GREEN);
    test_equal_i(traffic_light_next(GREEN), YELLOW);
    test_equal_i(traffic_light_next(YELLOW), RED);
}
```

8. Examples and Expected Results

- Program compiles with stub, but produces failed test cases

```
traffic_light.c, line 18: Actual value 0 differs from expected value 1.
traffic_light.c, line 19: Actual value 0 differs from expected value 2.
traffic_light.c, line 20: check passed
2 of 3 tests failed.
```

- Note: Output is integer values, not enumeration names

```
enum TrafficLight {
    RED,            ← 0
    RED_YELLOW,     ← 1
    GREEN,          ← 2
    YELLOW          ← 3
};
```

9. Function Body

- Implementation of the function

```
// Produces the next color of a traffic light
// given the current color of the traffic light.
enum TrafficLight traffic_light_next(enum TrafficLight tl) {
    if (tl == RED) {
        return RED_YELLOW;
    } else if (tl == RED_YELLOW) {
        return GREEN;
    } else if (tl == GREEN) {
        return YELLOW;
    } else if (tl == YELLOW) {
        return RED;
    }
    return RED;
}
```

10. Testing

- Main function call test function

```
int main(void) {
    traffic_light_next_test();
    return 0;
}
```

- Test results

```
traffic_light.c, line 18: check passed
traffic_light.c, line 19: check passed
traffic_light.c, line 20: check passed
traffic_light.c, line 21: check passed
All 4 tests passed!
```

11. Review and Revise

- Review the products of the steps
  - Improve function name
  - Improve parameter names
  - Improve purpose statement
  - Improve and extend tests

- Improve / generalize the function
  - switch-statement

Switch-Statement to Handle Multiple Cases

- Handle the cases of an enumeration
  - Compiler can check that all cases of enumeration are handled
- Example

```
enum TrafficLight traffic_light_next(enum TrafficLight tl) {
    switch (tl) {
        case RED: return RED_YELLOW;
        case RED_YELLOW: return GREEN;
        case GREEN: return YELLOW;
        case YELLOW: return RED;
    }
    return RED;
}
```

Selection in C: Switch-Statement

- Multi-way decision
- Tests for equality of an expression to integer constants

```
switch (expression) {
    case const-expression:
        statements; break;
    case const-expression:
        statements; break;
    ...
    default: statements
}
```

case handles explicit cases

default handles all other cases (similar to else)

- **break** statement exits from switch statement
- "Falls through" without break statement!

The Switch-Statement is Dangerous

- Use with constant integer cases only!
- Use break or return to avoid falling-through cases!

Switch-Statement Falls Through! Break!

Enters all cases after first matching case, unless break or return

```
enum TrafficLight traffic_light_next(enum TrafficLight tl) {
    switch (tl) {
        case RED:
            ...
            break;    ← leave the switch-statement!
        case RED_YELLOW:
            ...
            break;    ← leave the switch-statement!
        case GREEN:
            ...
            break;    ← leave the switch-statement!
        case YELLOW:
            ...
            break;    ← leave the switch-statement!
    } ...
}
```

Type Definitions and Enumerations

- Enumeration

```
enum TrafficLight {
    RED, RED_YELLOW, GREEN, YELLOW
};
```

- Type definition

```
typedef enum TrafficLight TrafficLight;     ← typedef <construct> NewName
```

- Can now declare function as

```
TrafficLight traffic_light_next(TrafficLight tl)
```

- instead of

```
enum TrafficLight traffic_light_next(enum TrafficLight tl)
```

RECIPE FOR INTERVALS

Intervals

- Intervals represent one or more ranges of numbers
- Pay attention to boundary cases
- Data definitions
  - Enumerations to name each interval
  - Constants to define boundaries

2. Data Definition

- How should domain information be represented as data in the program? How to interpret the data as real-world information?
- Data definition

```
enum TaxStage { // name each interval
    NO_TAX,
    LOW_TAX,
    HIGH_TAX
};

typedef int Euro; // int represents Euro

// interval boundaries
const Euro LOW_TAX_BOUNDARY  =  1000; // interpret.: price in Euro

const Euro HIGH_TAX_BOUNDARY = 10000; // interpret.: price in Euro
```

may omit typedef and use int directly

9. Function Body

- Implementation of the function

```
// Return the amount of tax for the given price.
int sales_tax(int price) {
    if (0 <= price && price < 1000) { // NO_TAX: [0, 1000)
        return 0;
    } else if (1000 <= price && price < 10000) { // LOW_TAX: [1000, 10000)
        return round_to_int(0.05 * price);
    } else if (price >= 10000) { // HIGH_TAX: [10000, ∞)
        return round_to_int(0.10 * price);
    }
    printsln("sales_tax, error: negative price");
    exit(1); // stop the program
}
```

or: Euro sales_tax(Euro price)

11. Review and Revise: Constants

```
const double LOW_TAX_RATE = 0.05;
const double HIGH_TAX_RATE = 0.10;
// Return the amount of tax for the given price.
int sales_tax(int price) {
    if (price < 0) {
        printsln("sales_tax, error: negative price");
        exit(1);
    } else if (price < LOW_TAX_BOUNDARY) { // NO_TAX: [0, 1000)
        return 0;
    } else if (price < HIGH_TAX_BOUNDARY) { // LOW_TAX: [1000, 10000)
        return round_to_int(LOW_TAX_RATE * price);
    } else { // HIGH_TAX: [10000, ∞)
        return round_to_int(HIGH_TAX_RATE * price);
    }
}
```

Summary

- Binary, octal, hexadecimal, and decimal numbers
- Data types and sizes
- Operators, precedence, and associativity
- Type conversions
- Expressions, evaluation diagrams
- Recipe for enumerations
- Recipe for intervals

C Keywords (ANSI C, ISO C89)

auto	**double**	**int**	struct
break	**else**	**long**	**switch**
case	**enum**	register	**typedef**
char	extern	**return**	union
const	**float**	**short**	**unsigned**
continue	for	**signed**	**void**
default	goto	**sizeof**	volatile
do	**if**	static	**while**

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9:00 Uhr

LIVE SESSION

Review

- Binary, octal, hexadecimal, and decimal numbers
  - Place-value notation
- Data types and sizes
  - How to interpret bit patterns, value ranges, floating-point representation
- Operators, precedence, and associativity
  - Infix expressions require definition of operator precedence
- Type conversions
  - Extend / restrict representation
- Expressions, evaluation diagrams
  - Stepwise evaluation of expressions
- Recipe for enumerations
- Recipe for intervals

Wert von x?

```
double x = 8 / 9;
```

Wert von x?

```
double x = 11 / 10;
```

Wert von x?

```
double x = 11.0 / 10;
```

Wert von x?

```
double x = (double) 11 / 10;
```

Integer Divide vs. Double Divide

```
int i = 1;              mov dword ptr [rbp - 8], 1     # copy 1 to int i
int j = 2;              mov dword ptr [rbp - 12], 2    # copy 2 to int j
                        mov eax, dword ptr [rbp - 8]   # copy int i to eax
                        cdq # sign-extend eax to edx:eax (conv. double word to quad word)
int k = i / j;          idiv dword ptr [rbp - 12]      # signed integer divide
                                                       # of edx:eax by m32 (int j)
                        mov dword ptr [rbp - 16], eax  # store result in int k
```

Integer Divide vs. Double Divide

```
                     LCPI0_0: .quad 4611686018427387904 # double y = 2;
                     LCPI0_1: .quad 4607182418800017408 # double x = 1;
                     ...
                     movsd xmm0, qword ptr [rip + LCPI0_0] # copy 2.0 to xmm0
                     movsd xmm1, qword ptr [rip + LCPI0_1] # copy 1.0 to xmm1
double x = 1;        movsd qword ptr [rbp - 24], xmm1 # copy 1.0 to double x
double y = 2;        movsd qword ptr [rbp - 32], xmm0 # copy 2.0 to double y
                     movsd xmm0, qword ptr [rbp - 24] # copy double x to xmm0
double z = x / y;    divsd xmm0, qword ptr [rbp - 32] # divide xmm0 (double x)
                                                      # by m64 (double y)
                     movsd qword ptr [rbp - 40], xmm0 # store result in double z
```

Stellenwertsystem

- Value of a symbol depends on its position

$$h_m h_{m-1} \cdots h_0 . h_{-1} \cdots h_{-n} = \sum_{i=-n}^{m} h_i \cdot b^i \quad m,n,b \in N \quad h_i \in \{0,1,\ldots,b-1\}$$

- Decimal system
  - Base b=10 (decimal)
  - Digit at position i is multiplied by 10^i
  - **Example:** 123.45_{10} means $1*10^2 + 2*10^1 + 3*10^0 + 4*10^{-1} + 5*10^{-2}$
- Binary system
  - Base b=2 (binary, dual)
  - Digit at position i is multiplied by 2^i
  - **Example:** 101.101_2 means $1*2^2 + 0*2^1 + 1*2^0 + 1*2^{-1} + 0*2^{-2} + 1*2^{-3}$

Binary Octal, Hexadecimal and Decimal

- Binary to Octal and Hexadecimal

octal	0			5			7			2		
binary	0	0	0	1	0	1	1	1	1	0	1	0
hexadecimal	1				7				A			

$$
\begin{aligned}
& 0*8^3 + 5*8^2 + 7*8^1 + 2*8^0 \\
&= 2^8 + 2^6 + 2^5 + 2^4 + 2^3 + 2^1 \\
&= 1*16^2 + 7*16^1 + 10*16^0 \\
&= 378
\end{aligned}
$$

Typical Sizes of Built-in Data Types

- C size rules (number of bits in memory)
  - char < short ≤ int ≤ long
  - 8 bits ≤ char, 16 bits ≤ short, 16 bits ≤ int, 32 bits ≤ long
- Actual size depends on hardware (see <limits.h>, <float.h>)
- Typical integer sizes and ranges

char	8 bits	$-2^{7}..2^{7}-1$	-128..127
unsigned char	8 bits	$0..2^{8}-1$	0..255
short	16 bits	$-2^{15}..2^{15}-1$	-32768..32767
unsigned short	16 bits	$0..2^{16}-1$	0..65535
int	32 bits	$-2^{31}..2^{31}-1$	-2147483648..2147483647
unsigned int	32 bits	$0..2^{32}-1$	0..4294967295
long	64 bits	$-2^{63}..2^{63}-1$	
unsigned long	64 bits	$0..2^{64}-1$	

Pingo: https://pingo.coactum.de/994545

Evaluating Complicated Expressions

4 < 8 && 21 + 3 != 10

- Recommendations
  - For readability add parentheses to make the order of evaluation explicit (...)
  - Simplify expressions
  - Use multiple simpler expressions

Precedence	Operators
highest	( ) [ ] -> .
	! ~ ++ -- +-(unary) *(value of)
	* / %
	+ -
	<< >>
	< <= > >=
	== !=
	&
	^
	|
	&&
	||
	?:
	= += -= *= /= %= &= ^= |=
lowest	,

Evaluating Complicated Expressions

4 < 8 && 21 + 3 != 10
4 < 8 && 24 != 10
1 && 24 != 10
1 && 1
1

- Recommendations
  - For readability add parentheses to make the order of evaluation explicit (...)
  - Simplify expressions
  - Use multiple simpler expressions

<table>
<tr><th>Precedence</th><th>Operators</th></tr>
<tr><td>highest</td><td>( ) [ ] -> .</td></tr>
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<tr><td></td><td><< >></td></tr>
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<tr><td></td><td>== !=</td></tr>
<tr><td></td><td>&</td></tr>
<tr><td></td><td>^</td></tr>
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<tr><td></td><td>= += -= *= /= %= &= ^= |=</td></tr>
<tr><td>lowest</td><td>,</td></tr>
</table>

Type conversions when evaluating expressions

double d; float f; char c; int i; long l;

```
  c    *   i  + d
char * int + double
 int * int + double
    int    + double
 double    + double
       double
```

Type conversions when evaluating expressions

double d; float f; char c; int i; long l;

```
(c      -   '0'  ) * 3.14
(char  - char)  * double
( int    -  int  ) * double
     int           * double
   double          * double
          double
```

Type Conversions in Assignments and for Arguments

- Conversion rules also apply across assignments
  - int i; char c;
  - i = c; // sign extension depends on whether char on machine is signed
  - c = i; // high-order bits are dropped

- … and when passing arguments to functions
  - double sqrt(double x); // method declaration
  - int i = 5;
  - int j = sqrt(i); // convert i to double