System-Level Programming

7 Operations & Expressions

J. Kleinöder, D. Lohmann, V. Sieh, P. Wägemann

Lehrstuhl für Informatik 4
Systemsoftware

Friedrich-Alexander-Universität
Erlangen-Nürnberg

Summer Term 2024

http://sys.cs.fau.de/lehre/ss24

07-Operatoren_en

Arithmetic Operators [=Java]

- Can be used with all integer and floating-point types

$+$	addition	
$-$	subtraction	
$\star$	multiplication	
$/$	division	
unary $-$	negative sign (e. g., $-a$)	$\leadsto$ multiplication with -1
unary $+$	positive sign (e. g., $+3$)	$\leadsto$ no effect

- Additionally only for integer types:

%	modulo (remainder of division)

Increment/Decrement Operators

- Available for integer types and pointers

++	increment (increase by 1)
−−	decrement (decrease by 1)

- Left-side operator (prefix) `++x` or `--x`
  - first, the value of variable `x` gets changed
  - then, the (new) value of `x` is used
- Right-side operator (postfix) `x++` or `x--`
  - first, the (old) value of `x` is used
  - then, the value of `x` gets changed
- Examples

```
a = 10;
b = a++;  // b: 10, a: 11
c = ++a;  // c: 12, a: 12
```

07-Operatoren_en

Comparison Operators [=Java]

- Comparison of two expressions

<	less
<=	less or equal
>	greater
>=	greater or equal
==	identical (two equal signs!)
!=	unequal

- Note: The result is of type `int` [≠Java]
  - Result: *false* $\mapsto$ 0
    true $\mapsto$ 1
  - The result can be used for calculations
- Examples

```
if (a >= 3) {···}
if (a == 3) {···}
return a * (a > 0);   // return 0 if a is negative
```

Logic Operators [≈Java]

- Combining logical values (true / false), commutative

&&	"and" (conjunction)	*true* && *true* → *true* *true* && *false* → *false* *false* && *false* → *false*
||	"or" (disjunction)	*true* || *true* → *true* *true* || *false* → *true* *false* || *false* → *false*
!	"not" (negation, unary)	! *true* → *false* ! *false* → *true*

- Note: operands and result are of type `int` [≠Java]
  - Operand (input parameter): $0 \mapsto$ *false*, $\neq 0 \mapsto$ *true*
  - Result: *false* $\mapsto 0$, *true* $\mapsto 1$

Logical Operators – Evaluation [=Java]

- The evaluation of a logical expression is terminated as soon as the result is known
  - Let `int a = 5; int b = 3; int c = 7;`

$$\underbrace{\underbrace{a > b}_{1} \;||\; \underbrace{a > c}_{?}}_{1} \quad \longleftarrow$$

will not be evaluated since the first term already is *true*

$$\underbrace{\underbrace{a > c}_{0} \;\&\&\; \underbrace{a > b}_{?}}_{0} \quad \longleftarrow$$

will not be evaluated since the first term already is *false*

- This *short-circuit evaluation* can have surprising results if subexpressions have side effects!

```
int a = 5; int b = 3; int c = 7;
if ( a > c && !func(b) ) {···}      // func() will not be called
```

07-Operatoren_en

Assignment Operators [=Java]

- General assignment operator (=)
  - assigns a value to a variable
  - example: `a = b + 23`
- Arithmetic assignment operators (+=, −=, ...)
  - shortened notation for modifying the value of a variable
  - example: `a += 23` is equivalent to `a = a + 23`
  - generally: `a` *op*`=` `b` is equivalent to `a = a` *op* `b`

    for *op* $\in \{ +, -, \star, /, \%, <<, >>, \&, \hat{}, | \}$
- Examples

```
int a = 8;
a += 8;     // a: 16
a %= 3;     // a: 1
```

Assignments are Expressions!

- Assignments can be nested in more complex expressions
  - The result of an assignment is the assigned value.

```
int a, b, c;
a = b = c = 1;  // c: 1, b: 1, a: 1
```

  - The use of assignments in arbitrary expressions leads to **side effects**, which are not always obvious.

```
a += b += c;    // Value of a and b?
```

Assignments are Expressions!

- Assignments can be nested in more complex expressions
  - The result of an assignment is the assigned value.

```
int a, b, c;
a = b = c = 1;  // c: 1, b: 1, a: 1
```

  - The use of assignments in arbitrary expressions leads to **side effects**, which are not always obvious.

```
a += b += c;    // Value of a and b?
```

Particularly dangerous: use of = instead of ==

In C, logical values are integers: $0 \mapsto$ *false*, $\emptyset \mapsto$ *true*

- Typical "rookie mistake" of control structures:

```
if (a = 6) {···} else {···} // BUG: if-branch is always taken!!!
```

- Compiler possibly gives **no warning** about the construct as it is a valid expression! $\leadsto$ Programming bug is quite easy to miss!

- Bit-wise operations of integers, commutative

&	bit-wise "and" (bit intersection)	$1 \,\&\, 1 \rightarrow 1$ $1 \,\&\, 0 \rightarrow 0$ $0 \,\&\, 0 \rightarrow 0$
|	bit-wise "or" (bit unification)	$1 \mid 1 \rightarrow 1$ $1 \mid 0 \rightarrow 1$ $0 \mid 0 \rightarrow 0$
∧	bit-wise "exclusive or" (bit antivalence)	$1 \wedge 1 \rightarrow 0$ $1 \wedge 0 \rightarrow 1$ $0 \wedge 0 \rightarrow 0$
~	bit-wise inversion (one's complement, unary)	$\sim 1 \rightarrow 0$ $\sim 0 \rightarrow 1$

Bit Operations (continued) [=Java]

- Shift operators on integers, not commutative

`<<`	bit-wise left shift (on the right side, 0 bits are “inserted”)
`>>`	bit-wise right shift (on the left side, 0 bits are “inserted”)

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
`x=156`	1	0	0	1	1	1	0	0	`0x9c`

- Shift operators on integers, not commutative

`<<`	bit-wise left shift (on the right side, 0 bits are "inserted")
`>>`	bit-wise right shift (on the left side, 0 bits are "inserted")

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
`x=156`	1	0	0	1	1	1	0	0	`0x9c`
`~x`	0	1	1	0	0	0	1	1	`0x63`

- Shift operators on integers, not commutative

`<<`	bit-wise left shift (on the right side, 0 bits are "inserted")
`>>`	bit-wise right shift (on the left side, 0 bits are "inserted")

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
`x=156`	1	0	0	1	1	1	0	0	`0x9c`
`~x`	0	1	1	0	0	0	1	1	`0x63`
`7`	0	0	0	0	0	1	1	1	`0x07`
`x | 7`	1	0	0	1	1	1	1	1	`0x9f`

- Shift operators on integers, not commutative

`<<`	bit-wise left shift (on the right side, 0 bits are "inserted")
`>>`	bit-wise right shift (on the left side, 0 bits are "inserted")

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
`x=156`	1	0	0	1	1	1	0	0	`0x9c`
`~x`	0	1	1	0	0	0	1	1	`0x63`
`7`	0	0	0	0	0	1	1	1	`0x07`
`x | 7`	1	0	0	1	1	1	1	1	`0x9f`
`x & 7`	0	0	0	0	0	1	0	0	`0x04`

Bit Operations (continued)

- Shift operators on integers, not commutative

<<	bit-wise left shift (on the right side, 0 bits are "inserted")
>>	bit-wise right shift (on the left side, 0 bits are "inserted")

- Examples (let x be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
x=156	1	0	0	1	1	1	0	0	0x9c
~x	0	1	1	0	0	0	1	1	0x63
7	0	0	0	0	0	1	1	1	0x07
x | 7	1	0	0	1	1	1	1	1	0x9f
x & 7	0	0	0	0	0	1	0	0	0x04
x ^ 7	1	0	0	1	1	0	1	1	0x9B

- Shift operators on integers, not commutative

`<<`	bit-wise left shift (on the right side, 0 bits are "inserted")
`>>`	bit-wise right shift (on the left side, 0 bits are "inserted")

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
x=156	1	0	0	1	1	1	0	0	0x9c
~x	0	1	1	0	0	0	1	1	0x63
7	0	0	0	0	0	1	1	1	0x07
x | 7	1	0	0	1	1	1	1	1	0x9f
x & 7	0	0	0	0	0	1	0	0	0x04
x ^ 7	1	0	0	1	1	0	1	1	0x9B
x << 2	0	1	1	1	0	0	0	0	0x70

- Shift operators on integers, not commutative

<<	bit-wise left shift (on the right side, 0 bits are “inserted”)
>>	bit-wise right shift (on the left side, 0 bits are “inserted”)

- Examples (let `x` be of type `uint8_t`)

bit#	7	6	5	4	3	2	1	0	
x=156	1	0	0	1	1	1	0	0	0x9c
~x	0	1	1	0	0	0	1	1	0x63
7	0	0	0	0	0	1	1	1	0x07
x | 7	1	0	0	1	1	1	1	1	0x9f
x & 7	0	0	0	0	0	1	0	0	0x04
x ^ 7	1	0	0	1	1	0	1	1	0x9B
x << 2	0	1	1	1	0	0	0	0	0x70
x >> 1	0	1	0	0	1	1	1	0	0x4e

Bit Operations – Usage

- By combining these operations, single bits are set/unset.

bit#	7	6	5	4	3	2	1	0
`PORTD`	?	?	?	?	?	?	?	?

Bit 7 shall be changed without altering other bits!

Bit Operations – Usage

- By combining these operations, single bits are set/unset.

bit#	7	6	5	4	3	2	1	0	
`PORTD`	?	?	?	?	?	?	?	?	Bit 7 shall be changed without altering other bits!
`0x80`	1	0	0	0	0	0	0	0	One bit gets set by **or-operation** with a mask that only contains a 1 bit at the desired position
`PORTD |= 0x80`	1	?	?	?	?	?	?	?	

Bit Operations – Usage

- By combining these operations, single bits are set/unset.

bit#	7	6	5	4	3	2	1	0	
`PORTD`	?	?	?	?	?	?	?	?	Bit 7 shall be changed without altering other bits!
`0x80`	1	0	0	0	0	0	0	0	One bit gets set by **or-operation** with a mask that only contains a 1 bit at the desired position
`PORTD |= 0x80`	1	?	?	?	?	?	?	?	
`~0x80`	0	1	1	1	1	1	1	1	One bit gets unset (set to 0) by **and-operation** with a mask that only contains a 0 bit at the desired position.
`PORTD &= ~0x80`	0	?	?	?	?	?	?	?	

Bit Operations – Usage

- By combining these operations, single bits are set/unset.

bit#	7	6	5	4	3	2	1	0	
`PORTD`	?	?	?	?	?	?	?	?	Bit 7 shall be changed without altering other bits!
`0x80`	1	0	0	0	0	0	0	0	One bit gets set by **or-operation** with a mask that only contains a 1 bit at the desired position
`PORTD |= 0x80`	1	?	?	?	?	?	?	?	
`~0x80`	0	1	1	1	1	1	1	1	One bit gets unset (set to 0) by **and-operation** with a mask that only contains a 0 bit at the desired position.
`PORTD &= ~0x80`	0	?	?	?	?	?	?	?	
`0x08`	0	0	0	0	1	0	0	0	Inversion of one bit by **xor-operation** with a mask that only contains a 1 bit at the desired position.
`PORTD ^= 0x08`	?	?	?	?	¿	?	?	?	

Bit Operations – Usage (continued)

- Bit masks are usually given as hexadecimal literals.

bit#	7	6	5	4	3	2	1	0
`0x8f`	1	0	0	0	1	1	1	1

$$\underbrace{1\,0\,0\,0}_{\texttt{8}}\;\underbrace{1\,1\,1\,1}_{\texttt{f}}$$

hex digit represents half byte: *nibble*

Bit Operations – Usage (continued)

- Bit masks are usually given as hexadecimal literals.

bit#	7	6	5	4	3	2	1	0
0x8f	1	0	0	0	1	1	1	1
	8				f			

hex digit represents half byte: *nibble*

- For "thinkers in decimals", the left-shift notation is more suitable

```
PORTD |= (1<<7);    // set bit 7:  1<<7 --> 10000000
PORTD &= ~(1<<7);   // mask bit 7: ~(1<<7) --> 01111111
```

Bit Operations – Usage (continued)

- Bit masks are usually given as hexadecimal literals.

bit#	7	6	5	4	3	2	1	0
0x8f	1	0	0	0	1	1	1	1
	8				f			

hex digit represents half byte: *nibble*

- For “thinkers in decimals”, the left-shift notation is more suitable

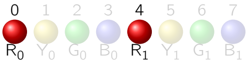
```
PORTD |= (1<<7);    // set bit 7:  1<<7 --> 10000000
PORTD &= ~(1<<7);   // mask bit 7: ~(1<<7) --> 01111111
```

- Combined with the or-operation, shifting ones works for complex masks

```
#include <led.h>
void main(void) {
  uint8_t mask = (1<<RED0) | (1<<RED1);

  sb_led_setMask (mask);

  while(1) ;
}
```

⇝ 

Conditional Evaluation

- Formulation of conditions in expressions

  expression$_1$ **?** *expression*$_2$ **:** *expression*$_3$

  - first, *expression*$_1$ gets evaluated
    - *expression*$_1$ $\neq 0$ (*true*) $\leadsto$ *expression*$_2$ is the result
    - *expression*$_1$ $= 0$ (*false*) $\leadsto$ *expression*$_3$ is the result
  - `?:` is the only ternary (three-part) operator in C

- Example

```
int abs(int a) {
  // if (a<0) return -a; else return a;
  return (a<0) ? -a : a;
}
```

Sequence Operator [$\neq$Java]

- Sequencing of expressions

  expression$_1$ **,** *expression*$_2$

  - first, *expression*$_1$ gets evaluated
    $\leadsto$ side effects of *expression*$_1$ are visible for *expression*$_2$
  - the value of *expression*$_2$ is the result

- Use of the comma operator is often not required!
  (C-preprocessor macros with side effects)

Associativity Rules of Operators [≈Java]

<table>
<tr><th></th><th>class</th><th>operators</th><th>associativity</th></tr>
<tr><td>1</td><td>function call, array access
structure access
post-increment/-decrement</td><td>x() x[]
x.y x->y
x++ x--</td><td>left → right</td></tr>
<tr><td>2</td><td>pre-increment/-decrement
unary operators
address, pointer
type conversion (cast)
type size</td><td>++x --x
+x -x ~x !x
& ∗
(<Typ>)x
sizeof(x)</td><td>right → left</td></tr>
<tr><td>3</td><td>multiplication, division, modulo</td><td>∗ / %</td><td>left → right</td></tr>
<tr><td>4</td><td>addition, subtraction</td><td>+ -</td><td>left → right</td></tr>
<tr><td>5</td><td>bit-wise shifts</td><td>>> <<</td><td>left → right</td></tr>
<tr><td>6</td><td>relational operators</td><td>< <= > >=</td><td>left → right</td></tr>
<tr><td>7</td><td>equality operators</td><td>== !=</td><td>left → right</td></tr>
<tr><td>8</td><td>bit-wise AND</td><td>&</td><td>left → right</td></tr>
<tr><td>9</td><td>bit-wise OR</td><td>|</td><td>left → right</td></tr>
<tr><td>10</td><td>bit-wise XOR</td><td>^</td><td>left → right</td></tr>
<tr><td>11</td><td>conjunction</td><td>&&</td><td>left → right</td></tr>
<tr><td>12</td><td>disjunction</td><td>||</td><td>left → right</td></tr>
<tr><td>13</td><td>conditional evaluation</td><td>?:=</td><td>right → left</td></tr>
<tr><td>14</td><td>assignment</td><td>= op=</td><td>right → left</td></tr>
<tr><td>15</td><td>sequence</td><td>,</td><td>left → right</td></tr>
</table>

Type Promotion in Expressions

- Operations are calculated *at least* with `int`-width
  - `short`- and `signed char`-operands are “promoted” implicitly (↪ *Integer Promotion*)
  - Only the result will then be promoted/cut off to match the target type

```
int8_t a=100, b=3, c=4, res;   // range: -128 --> +127
```

$$\underbrace{\texttt{res}}_{\texttt{int8\_t: 75}} = \underbrace{\underbrace{\underbrace{\texttt{a}}_{\texttt{int: 100}} * \underbrace{\texttt{b}}_{\texttt{int: 3}}}_{\texttt{int: 300}} / \underbrace{\texttt{c}}_{\texttt{int: 4}}}_{\texttt{int: 75}}\ ;$$

```
// promotion to int: 300 fits in!
```

Type Promotion in Expressions (continued)

- In general, the *largest* involved width is used

```
int8_t a=100, b=3, res;   // range: -128 --> +127
int32_t c=4;              // range: -2147483648 --> +2147483647

res = a * b / c; // promotion to int32_t
```

```
int8_t: 75    int: 100    int: 3
              int: 300
              int32_t: 300
              int32_t: 75
```

Type Casting in Expressions (continued)

- Floating-point types are thereby considered to be "larger" than integer types
- All floating point operations are *at least* calculated with `double` width

```
  int8_t a=100, b=3, res;            // range: -128 --> +127

  res     =   a      *   b     /   4.0f   ; // promotion to double
int8_t: 75  int: 100   int: 3   double 4.0
              int: 300
              double: 300.0
                   double: 75.0
```

Type Promotion in Expressions (continued)

- `unsigned` types are also considered "larger" than `signed` types

```
int s = -1, res;          // range: -32768 --> +32767
unsigned u = 1;           // range: 0 --> 65535

res  =    s     < u;      // promotion to unsigned: -1 --> 65535
```

$\underbrace{\texttt{res}}_{\texttt{int: 0}} = \underbrace{\underbrace{\texttt{s}}_{\texttt{unsigned: 65535}} \texttt{ < u}}_{\texttt{unsigned: 0}}\texttt{;}$

⇝ Surprising results when using negative values!

⇝ Avoid mixing `signed` and `unsigned` operands!

Type Casting in Expressions – Type Casts

- By using the type cast operator, an expression is converted into a target type.
- Casting is explicit type promotion.

  (*type***)** *expression*

```
int s = -1, res;        // range: -32768 --> +32767
unsigned u = 1;         // range: 0 --> 65535

res  = s < (int) u;     // cast u to int
int: 1       int: 1
          int: 1
```

References

[GDI] Frank Bauer. *Grundlagen der Informatik*. Vorlesung. Friedrich-Alexander-Universität Erlangen-Nürnberg, Lehrstuhl für Informatik 5, 2015 (jährlich). URL: `https://gdi.cs.fau.de/w15/material`.