

Solution to Exercise 68.

- a) *// POST: return value is the maximum of i, j and k*
- b) *// PRE: 0 not contained in {i, ..., j}*
// POST: return value is the sum 1/i + 1/(i+1) + ... + 1/j

Solution to Exercise 69.

- a) If i is odd, the execution does not reach a return statement, and the function call expression is invalid. It seems that we want a function that returns true if and only if i is even. This can be done as follows.

```
bool is_even (int i)
{
    // POST: return value is true if and only if i is even
    return (i % 2 == 0);
}
```

- b) If x has value 0, result will never be set to a defined value. The corresponding function call expression has undefined value. To fix this, we can either make $x \neq 0.0$ a precondition (but then we don't have to check it like the function does it), or we can invent some return value for the case where x has value 0. In any case, we don't need the variable result. Here are the two variants.

```
double inverse (double x)
{
    // PRE: x != 0
    // POST: return value is 1/x
    return 1.0 / x;
}
```

```
double inverse (double x)
{
    // POST: return value is 1/x for x != 0, and 0 otherwise
    if (x != 0.0)
        return 1.0 / x;
    else
        return 0.0;
}
```

Solution to Exercise 70. The program outputs the 7-th power of the input value i . The computation takes place in the function g that multiplies i with $f(i)$ (i^2) and $f(f(i))$ (i^4).

Solution to Exercise 71. Here are the three problems.

- a) The call of $g(2.0 * x)$ in the function body of f is not in the scope of the function g , since that function is only declared later through its definition. Consequently, g cannot be used in f .
- b) In the function g , the modulus operator is used with double operands, but for floating point number type operands, there is no modulus operator.
- c) The function body of h is not in the scope of the variable $result$, since that variable is only declared later. Consequently, $result$ cannot be used in h .

Solution to Exercise 72.

```

1 // Program: fpsys2.C
2 // Provide a graphical representation of floating point numbers
3
4 #include <iostream>
5 #include <cmath>
6 #include <IFM/window>
7
8
9 int main()
10 {
11     // Input parameters of floating point system
12     std::cout << "Draw F(2,p,e_min,e_max).\np =? ";
13     unsigned int p;
14     std::cin >> p;
15     std::cout << "e_min =? ";
16     int emin;
17     std::cin >> emin;
18     std::cout << "e_max =? ";
19     int emax;
20     std::cin >> emax;
21
22     // compute the smallest normalized significand 2^(p-1)
23     unsigned int smin = (unsigned int)(std::pow (2.0, double(p-1)));
24     // compute the largest normalized significand (2^p)-1
25     unsigned int smax = 2 * smin - 1;
26     // compute 2^emin
27     double pemmin = std::pow (2.0, double(emin));
28     // compute 2^emax
29     double pemmax = std::pow (2.0, double(emax));
30
31     // For each positive number x of the system draw a circle
32     // with radius x around the window center
33
34     // parameters to scale output
35     int cx = (ifm::wio.xmax() - ifm::wio.xmin()) / 2;
36     int cy = (ifm::wio.ymax() - ifm::wio.ymin()) / 2;
37     double scale = cx / (pemmax * smax);
38
39     // zero
40     ifm::wio << ifm::Point(cx, cy);
41     // loop over all normalized significands
42     for (unsigned int i = smin; i <= smax; ++i)
43         // loop over all exponents
44         for (double m = pemmin; m <= pemmax; m *= 2)
45             ifm::wio << ifm::Circle(cx, cy, int(m * i * scale));
46
47     ifm::wio.wait_for_mouse_click();

```

```
48     return 0;
49 }
```

Solution to Exercise 73. The program still works if $s(x) \geq \sqrt{x}$, so we only have a potential problem if $s(x) < \sqrt{x}$. Because $|s(x) - \sqrt{x}|$ equals $\sqrt{x} - s(x)$ in this case, the relative error bound gives us $\sqrt{x} - s(x) \leq \varepsilon\sqrt{x}$, and this implies

$$s(x) \geq (1 - \varepsilon)\sqrt{x} \geq \frac{1}{2}\sqrt{x}.$$

It follows that

$$2s(x) \geq \sqrt{x},$$

meaning that we can safely use `2*std::sqrt(n)` instead of `std::sqrt(n)` in Program 26. Note that $2s(x)$ is indeed representable as a floating point number again, since we have assumed the system to be binary.

Solution to Exercise 74. The desired number of twin primes is 58980 as the following program shows that implements the approach of a). It turns out that we have to use the fast prime number test from Program 26 in order not to wait too long (we still have to wait pretty long).

```
1  // Program: twinprimes.C
2  // Count twin primes in 2,...,10000000
3
4  #include <iostream>
5  #include <cmath>
6
7  bool is_prime (unsigned int n)
8  {
9      // POST: return value is true if and only if n is prime
10     if (n < 2) return false; // 0 and 1 are not prime
11
12     // Computation: test possible divisors d up to sqrt(n)
13     unsigned int bound = (unsigned int)(std::sqrt(n));
14     unsigned int d;
15     for (d = 2; d <= bound && n % d != 0; ++d);
16
17     // Output
18     return d > bound;
19 }
20
21 int main ()
22 {
23     // keep primality info for odd i and i+2
24     bool curr = false; // i = 1
25     bool next = true;  // i = 3
26     int twins = 0;     // number of twins
27     for (int i = 3; i < 9999999; i += 2) {
28         curr = next; // i
29         next = is_prime(i+2); // i+2
30         if (curr && next) ++twins;
31     }
32     std::cout << "Number of twin primes: " << twins << "\n";
```

```

33
34     return 0;
35 }

```

A much faster approach is based on *Eratosthenes's sieve*. We simply compute all prime numbers in the given range, and then use this information to select the twin primes:

```

1  // Program: twinprimes2.C
2  // Count twin primes in 2,...,10000000
3
4  #include <iostream>
5  #include <algorithm>
6
7  int main()
8  {
9      // definition and initialization: provides us with
10     // Booleans crossed_out[0],..., crossed_out[9999999]
11     bool crossed_out[10000000];
12     std::fill (crossed_out, crossed_out + 10000000, false);
13
14     // computation of all prime numbers in the range
15     for (unsigned int i = 2; i < 10000000; ++i)
16         if (!crossed_out[i])
17             // cross out all proper multiples of i
18             for (unsigned int m = 2*i; m < 10000000; m += i)
19                 crossed_out[m] = true;
20
21     // now count twin primes: (i-2, i) = (3,5) is first pair
22     unsigned int twins = 0;
23     for (unsigned int i = 5; i < 10000000; i+=2)
24         if (!crossed_out[i-2] && !crossed_out[i])
25             ++twins;
26
27     // output
28     std::cout << "Number of twin primes: " << twins << "\n";
29
30     return 0;
31 }

```

This shows that the subdivision of the task into subtasks according to a) is not appropriate in this case.

Solution to Exercise 75.

```

double pow (double b, int e)
{
    // PRE:  e >= 0 || b != 0.0
    // POST: return value is b^e
    double result = 1.0;
    if (e < 0) {
        // b^e = (1/b)^(-e)
        b = 1.0/b;
        e = -e;
    }
    // maintain bpow = b^(2^i), initialized for i=0

```

```

    for (double bpow = b; e != 0; e /= 2) {
        if (e % 2 == 1) result *= bpow;
        bpow *= bpow; // square bpow to get b^(2^(i+1))
    }
    return result;
}

```

Solution to Exercise 76.

```

1  #include <iostream>
2
3  // PRE: i_ptr and j_ptr point to existing objects
4  // POST: the values of these two objects are swapped
5  void swap (int* i_ptr, int* j_ptr)
6  {
7      int h = *i_ptr;
8      *i_ptr = *j_ptr;
9      *j_ptr = h;
10 }
11
12 int main() {
13     // input
14     std::cout << "i =? ";
15     int i; std::cin >> i;
16
17     std::cout << "j =? ";
18     int j; std::cin >> j;
19
20     // function call
21     swap(&i, &j);
22
23     // output
24     std::cout << "Values after swapping: i = " << i
25               << ", j = " << j << ".\n";
26
27     return 0;
28 }

```

Solution to Exercise 77. We simply take the sorting loop out of `sort_array.C` and put it into a function. At the same time, we move from iteration by index to iteration by pointers. A less elegant but also valid solution is to keep the original code with iteration by index, after computing `n` as last-first.

```

1  // Program: sort_array2.C
2  // read a sequence of n numbers into an array,
3  // sort them using a function, and output the
4  // sorted sequence
5  #include <iostream>
6  #include <algorithm>
7
8  // PRE: [first, last) is a valid range
9  // POST: the elements *p, p in [first, last) are
10 //      in ascending order
11 void sort (int* first, int* last)
12 {
13     // sort array: in round p=first,...,last-1 we find
14     // the smallest element in the range described by

```

```

15 // [p, last) and interchange it with *p
16 for (int* p = first; p != last; ++p) {
17     // find minimum in nonempty range described by [p, last)
18     int* p_min = p; // pointer to current minimum
19     int* q = p;     // pointer to current element
20     while (++q != last)
21         if (*q < *p_min) p_min = q;
22     // interchange *p with *p_min
23     std::iter_swap (p, p_min);
24 }
25 }
26
27 int main()
28 {
29     // input of n
30     unsigned int n;
31     std::cin >> n;
32
33     // dynamically allocate array
34     int* a = new int[n];
35
36     // read into the array
37     for (int i=0; i<n; ++i) std::cin >> a[i];
38
39     // sort
40     sort (a, a+n);
41
42     // output sorted sequence
43     for (int i=0; i<n; ++i) std::cout << a[i] << " ";
44     std::cout << "\n";
45
46     // delete array
47     delete[] a;
48
49     return 0;
50 }
51 }

```

Solution to Exercise 78. Given the input date, the main task is to count the number of days that have passed since January 1, 1900. Once we have that information, we can take the number modulo 7, and this determines the weekday.

Here is a list of the major subtasks (your list might be different).

1. find out whether the input date is legal;
2. count the number of days in all *years* preceding the input date;
3. count the number of days in all *months* preceding the input date (this has 2 as a subtask);
4. count the number of days preceding the input date (this has 3 as a subtask);
5. given this count, output the weekday.

Smaller subtasks needed by the above are the following.

1. find out whether a given year is a leap year;

2. find out how many days a given month has in a given year;
3. compute the weekday as a number in $\{0, \dots, 6\}$;
4. transform the number of a weekday into its name.

Here is the program resulting from this subdivision into subtasks.

```

1 // Prog: perpetual_calendar
2 // compute the weekday for any given date >= 01.01.1900 (Monday)
3
4 #include<iostream>
5 #include<cassert>
6
7 // PRE: year >= 1900
8 // POST: return value is true iff year is a leap year
9 // -----
10 bool is_leap_year (unsigned int year)
11 {
12     assert (year >= 1900);
13     return year % 4 == 0 && (year % 100 != 0 || year % 400 == 0);
14 }
15
16 // PRE: year >= 1900, 1 <= month <= 12
17 // POST: return value is the number of days in month.year
18 // -----
19 unsigned int days_in_month (unsigned int month, unsigned int year)
20 {
21     assert (year >= 1900);
22     assert (1 <= month && month <= 12);
23     static unsigned int days[12] =
24         {31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31};
25     return days[month-1] + (month==2 && is_leap_year (year));
26 }
27
28 // POST: return value is true iff day.month.year is
29 //       an existing date >= 01.01.1900
30 // -----
31 bool is_date (unsigned int day, unsigned int month, unsigned int year)
32 {
33     return
34         year >= 1900 && 1 <= month && month <= 12 &&
35         1 <= day && day <= days_in_month (month, year);
36 }
37
38
39 // PRE: year >= 1900
40 // POST: return value is the number of days in years [1900, ..., year)
41 // -----
42 unsigned int days_up_to_year (unsigned int year)
43 {
44     assert (year >= 1900);
45     unsigned int d = 0;
46     // the following could be done more efficiently, but why?
47     for (unsigned int y = 1900; y < year; ++y)
48         d += 365 + is_leap_year (y);
49     return d;
50 }
51
52 // PRE: year >= 1900, 1 <= month <= 12
53 // POST: return value is the number of days in
54 //       months [01.1900, ..., month.year)
55 // -----

```

```

56 unsigned int days_up_to_month (unsigned int month, unsigned int year)
57 {
58     assert (year >= 1900);
59     assert (1 <= month && month <= 12);
60     unsigned int days = days_up_to_year (year); // before year
61     for (unsigned int m = 1; m < month; ++m) // before month
62         days += days_in_month (m, year);
63     return days;
64 }
65
66 // PRE: is_date (day, month, year)
67 // POST: return value is the number of days in
68 //       [01.01.1900, ..., day.month.year)
69 // -----
70 unsigned int days_up_to (unsigned int day, unsigned int month,
71                         unsigned int year)
72 {
73     assert (is_date (day, month, year));
74     return days_up_to_month (month, year) + day - 1;
75 }
76
77 // PRE: is_date (day, month, year)
78 // POST: return value is weekday (0 = Monday, ..., 6 = Sunday)
79 // -----
80 unsigned int weekday (unsigned int day,
81                     unsigned int month,
82                     unsigned int year)
83 {
84     assert (is_date (day, month, year));
85     return days_up_to (day, month, year) % 7;
86 }
87
88 // PRE: weekday < 7
89 // POST: writes the name of the weekda to standard output
90 //       (0 = Monday, ..., 6 = Sunday)
91 // -----
92 void print_weekday (unsigned int weekday) {
93     assert (weekday < 7);
94     if (weekday == 0) std::cout << "Monday";
95     else if (weekday == 1) std::cout << "Tuesday";
96     else if (weekday == 2) std::cout << "Wednesday";
97     else if (weekday == 3) std::cout << "Thursday";
98     else if (weekday == 4) std::cout << "Friday";
99     else if (weekday == 5) std::cout << "Saturday";
100    else std::cout << "Sunday";
101    std::cout << "\n";
102 }
103
104 int main()
105 {
106     // input date
107     std::cout << "Compute weekday of date (day/month/year) for\n";
108     std::cout << "day =? ";
109     unsigned int day; std::cin >> day;
110     std::cout << "month =? ";
111     unsigned int month; std::cin >> month;
112     std::cout << "year =? ";
113     unsigned int year; std::cin >> year;
114
115     // check date
116     if (!is_date (day, month, year)) {
117         std::cout << "Illegal date.\n";
118         return 1;
119     }
120

```



```

121  // output weekday
122  print_weekday (weekday (day, month, year));
123
124  return 0;
125 }

```

Solution to Exercise 79. Here we show how it is done under Unix-type platforms and the g++ compiler. Let's assume that your home directory is /home/myhome/. Under this directory, you now create a subdirectory named libifm, with two subdirectories include and lib. In the subdirectory include, you create another subdirectory IFM.

Now you copy math.h into the include/IFM subdirectory and math.C into the lib subdirectory.

- (i) Build the object code. For this, go to the lib subdirectory and tell the compiler to generate the object code file math.o. For this, you type

```
g++ -I/home/myhome/libifm/include -c math.C
```

The directory after the -I is the one where the compiler will look for your include files. The path IFM/math.h in math.C is relative to that include directory. You can provide several include directories through several -I's.

- (ii) Build the library from the o-files in the lib subdirectory. For this, you type

```
ar r libmath.a *.o
```

This tells the archive program ar to put all object files found in the current directory into a single library called libmath.a.

- (iii) Build the executable from whatever directory you want, by typing

```
g++ -I/home/myhome/libifm/include -L/home/myhome/libifm/lib
callpow4.C -lmath -o callpow4
```

This tells g++ to compile (and link) the program callpow4.C, using the library libmath.a found in the directory that is specified after -L.

Solution to Exercise 80.

By the C++ standard, converting a floating point number to int cuts off the fractional part. Then we compute the error between the original number and its truncation. Under the IEEE standard 754, this difference has one significant digit less than and is therefore exactly representable as a double value, *unless* the input value is negative and has largest possible exponent. But in this case, the truncation is also out of range, and we don't care. Now we can exactly test whether the error is at most 0.5 (in which case we return the truncation), or more (in which case we return the next integer, going away from zero).

```

1  #include <iostream>
2
3  // POST: return value is the integer nearest to x; if there are
4  //       two nearest integers, the one closer to 0 is chosen
5  int round (double x)
6  {
7      int trunc = int(x); // rounds towards 0 by standard
8      double error = x - trunc; // note: result is exact!
9      if (error > 0.5)
10         // x was positive, and trunc + 1 is nearer
11         return trunc + 1;
12     if (error < -0.5)
13         // x was negative, and trunc - 1 is nearer
14         return trunc - 1;
15     // |error| <= 0.5, trunc is closest integer
16     return trunc;
17 }
18
19 int main ()
20 {
21     for (double d = -2; d <= 2; d += 0.25)
22         std::cout << "closest integer to " << d << " is "
23             << round (d) << "\n";
24
25     return 0;
26 }

```

As far as the integration into the library is concerned, please follow the procedure in the solution to Exercise 79 above.

Solution to Exercise 81. The code is subdivided into several functions. The most important function `deducible` tries to make one Sherlock-Holmes-type deduction for given r , c and n . It is repeatedly called by the function `fill_cell` for all values of r , c , and n ; if a deduction is found, `fill_cell` accordingly updates the board, a 3-dimensional array that maintains the information which numbers are candidates for which cells.

The function `deduce` tries the Sherlock-Holmes-type deductions in turn, where it distinguishes between deduction from row, column, or box in case 2.

```

1  // Prog: sudoku.C
2  // solves sudokus according to simple deduction heuristic (may fail)
3  #include <cassert>
4  #include <iostream>
5
6  // Here is the algorithm: given a partial filling of the 81 cells,
7  // we try to find a row r, a column c, and a number n such that n is
8  // the unique candidate to be filled into the empty cell (r,c) in row
9  // r and column c. There are two situations in which this is easy:
10 // 1. all numbers distinct from n already appear in the row, column,
11 //    or 3x3 box containing the cell (r,c)
12 // 2. we already know that n cannot appear in the other cells of the
13 //    row, column, or box containing (r,c)
14 // To check this, we maintain for every triple (r,c,n) the information
15 // whether n is still a candidate for cell (r,c). Whenever a cell is filled,
16 // we remove the filled number from the candidate list of all other cells
17 // in the same row, column, or box.
18
19 // the grid: a 3x3x3 array of boolean values, one for each triple (r,c,n)
20 // grid[r][c][0] == true iff cell (r,c) not filled yet
21 // grid[r][c][n] == true for n>0 iff n is still a candidate for cell (r,c)

```

```

22 bool grid[9][9][10];
23
24 // PRE: cell (r,c) is empty, and n>0 is a candidate for (r,c)
25 // POST: puts n into (r,c); removes n as candidate from all other cells
26 //       of the row, the column, and the box of (r,c); removes all
27 //       numbers distinct from n as candidates from (r,c)
28 void update_grid (unsigned int r, unsigned int c, unsigned int n)
29 {
30     // assert precondition
31     assert (grid[r][c][0] && n > 0 && grid[r][c][n]);
32     // go through row of (r,c)
33     for (unsigned int j=0; j<9; ++j)
34         grid[r][j][n] = false;
35     // go through column of (r,c)
36     for (unsigned int i=0; i<9; ++i)
37         grid[i][c][n] = false;
38     // go through box of (r,c)
39     unsigned int lr = r-r%3; // (lr, lc) is the lower left cell of
40     unsigned int lc = c-c%3; // this box
41     for (unsigned int i=lr; i<lr+3; ++i)
42         for (unsigned int j=lc; j<lc+3; ++j)
43             grid[i][j][n] = false;
44     // go through numbers
45     for (unsigned int m=0; m<10; ++m)
46         grid[r][c][m] = false;
47     // fill cell
48     grid[r][c][n] = true;
49 }
50
51 // POST: returns n > 0 if n is the unique candidate for cell (r,c) and
52 //       0 otherwise
53 int unique_number (unsigned int r, unsigned int c)
54 {
55     int n = 0;
56     bool found = false;
57     for (unsigned int m = 1; m<10; ++m)
58         if (grid[r][c][m]) {
59             if (found) return 0; // we've already seen a candidate
60             n = m; // this is the first candidate
61             found = true;
62         }
63     return n;
64 }
65
66 // PRE: cell (r,c) is empty, and n>0 is a candidate for (r,c)
67 // POST: returns true if and only if n is not a candidate for any
68 //       cell distinct from (r,c) within the same row
69 bool deducible_from_row (unsigned int r, unsigned int c, unsigned int n)
70 {
71     // assert preconditions
72     assert (grid[r][c][0] && n > 0 && grid[r][c][n]);
73     // go through the columns
74     for (int j=0; j<9; ++j)
75         if (j != c && grid[r][j][n]) return false; // candidate somewhere else
76     return true;
77 }
78
79 // PRE: cell (r,c) is empty, and n>0 is a candidate for (r,c)
80 // POST: returns true if and only if n is not a candidate for any
81 //       cell distinct from (r,c) within the same column
82 bool deducible_from_column (unsigned int r, unsigned int c, unsigned int n)
83 {
84     // assert preconditions
85     assert (grid[r][c][0] && n > 0 && grid[r][c][n]);
86     // go through the rows

```

```

87     for (int i=0; i<9; ++i)
88         if (i != r && grid[i][c][n]) return false; // candidate somewhere else
89     return true;
90 }
91
92 // PRE: cell (r,c) is empty, and n>0 is a candidate for (r,c)
93 // POST: returns true if and only if n is not a candidate for any
94 //        cell distinct from (r,c) within the same box
95 bool deducible_from_box (unsigned int r, unsigned int c, unsigned int n)
96 {
97     // assert preconditions
98     assert (grid[r][c][0] && n > 0 && grid[r][c][n]);
99     unsigned int lr = r-r%3; // (lr, lc) is the lower left cell of
100    unsigned int lc = c-c%3; // this box
101    // go through the box
102    for (int i=lr; i<lr+3; ++i)
103        for (int j=lc; j<lc+3; ++j)
104            if ( (i != r || j != c) && grid[i][j][n])
105                return false; // candidate somewhere else
106    return true;
107 }
108
109 // POST: returns true iff (r,c) is empty, n>0 is a candidate for (r,c), and
110 //        - n is the unique candidate for the cell (r,c), or
111 //        - n is deducible as the unique candidate from the row,
112 //        - column, or box of (r,c)
113 bool deducible (unsigned int r, unsigned int c, unsigned int n)
114 {
115     if (grid[r][c][0] && n > 0 && grid[r][c][n])
116         return
117             (n == unique_number (r,c)) || // unique candidate for (r,c) ?
118             deducible_from_row (r, c, n) ||
119             deducible_from_column (r, c, n) ||
120             deducible_from_box (r, c, n);
121     return false;
122 }
123
124 // POST: returns true if and only if there is an empty cell (r,c) and a
125 //        number n>0 such that n can be deduced to be the number to be
126 //        put into (r,c); if the return value is true, the grid is updated
127 //        by filling an empty cell with an accordingly deduced number
128 bool fill_cell()
129 {
130     for (unsigned int r=0; r<9; ++r)
131         for (unsigned int c=0; c<9; ++c)
132             for (unsigned int n=1; n<10; ++n)
133                 if (deducible (r, c, n)) {
134                     update_grid (r, c, n);
135                     return true;
136                 }
137     return false;
138 }
139
140 int main()
141 {
142     // set up empty grid
143     for (int r=0; r<9; ++r)
144         for (int c=0; c<9; ++c) {
145             for (int n=0; n<10; ++n)
146                 grid[r][c][n] = true;
147         }
148
149     // input: 9 x 9 numbers in {0,..,9} rowwise (0 means no number)
150     unsigned int filled_cells = 0; // total number of filled cells
151     for (int r=0; r<9; ++r)

```

```
152     for (int c=0; c<9; ++c) {
153         int n;
154         std::cin >> n;
155         if (n > 0) {
156             update_grid (r, c, n);
157             ++filled_cells;
158         }
159     }
160
161     // main loop
162     while (fill_cell()) ++filled_cells;
163
164     // sudoku is solved if all cells could be filled
165     if (filled_cells == 81)
166         std::cout << "Sudoku is solved:\n";
167     else
168         std::cout << "Could only fill " << filled_cells << " cells:\n";
169     // output solution in 3 x 3 blocks (0 means no number deduced);
170     for (unsigned int lr=0; lr<9; lr+=3) {
171         for (unsigned int r=lr; r<lr+3; ++r) {
172             for (unsigned int lc=0; lc<9; lc+=3) {
173                 for (unsigned int c=lc; c<lc+3; ++c)
174                     std::cout << unique_number (r, c) << " "; // blank after number
175                 std::cout << " "; // extra blank after every three columns
176             }
177             std::cout << "\n"; // extra line break after every third row
178         }
179         std::cout << "\n"; // line break after row
180     }
181 }
```
