12. Arrays II

Strings, Lindenmayer Systems, Multidimensional Arrays, Vectors of Vectors, Shortest Paths, Arrays and Vectors as Function Arguments

Texts

- can be represented with the type `std::string` from the standard library.
-
```
std::string text = "bool";
```

defines a string with length 4

- A string is conceptually an array with base type `char`, plus additional functionality
- Requires `#include <string>`

Strings: pimped `char`-Arrays

A `std::string`...

- knows its length

```
text.length()
```

returns its length as `int` (call of a member function; will be explained later

- can be initialized with variable length

```
std::string text (n, 'a')
```

`text` is filled with n `'a'`s

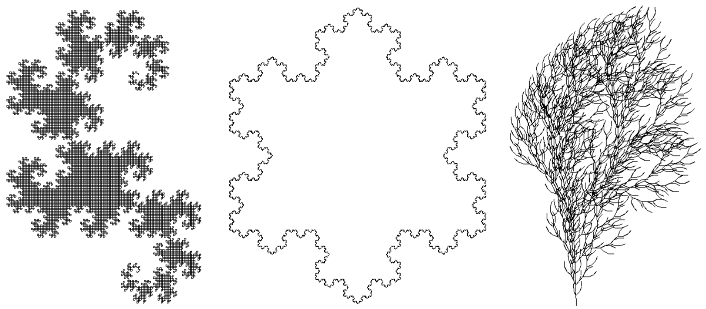
- "understands" comparisons

```
if (text1 == text2) ...
```

`true` if `text1` and `text2` match

Lindenmayer-Systems (L-Systems)

Fractals made from Strings and Turtles



L-Systems have been invented by the Hungarian biologist Aristid Lindenmayer (1925 – 1989) to model the growth of plants.

Definition and Example

- Alphabet Σ
- Σ^*: all finite words over Σ
- Production $P : \Sigma \to \Sigma^*$
- Initial word $s_0 \in \Sigma^*$

- $\{\mathrm{F}, +, -\}$
-

c	$P(c)$
F	F + F +
+	+
−	−

- F

Definition

The triple $\mathcal{L} = (\Sigma, P, s_0)$ is an L-System.

The Described Language

Words $w_0, w_1, w_2, \ldots \in \Sigma^*$:

$P(\mathrm{F}) = \mathrm{F} + \mathrm{F} +$

$$w_0 := s_0 \qquad w_0 := \mathrm{F}$$

$$\mathrm{F} + \mathrm{F} +$$

$$w_1 := P(w_0) \qquad w_1 := \boxed{\mathrm{F}}\boxed{+}\boxed{\mathrm{F}}\boxed{+}$$

$$w_2 := P(w_1) \qquad w_2 := \boxed{\mathrm{F} + \mathrm{F} +}\boxed{+}\boxed{\mathrm{F} + \mathrm{F} +}\boxed{+}$$

$$P(\mathrm{F})\,P(+)\,P(\mathrm{F})\,P(+)$$

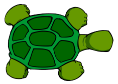
$$\vdots \qquad \vdots$$

Definition

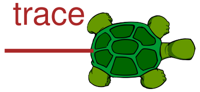
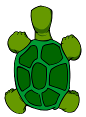
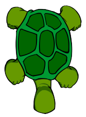
$P(c_1c_2\ldots c_n) := P(c_1)P(c_2)\ldots P(c_n)$

Turtle-Graphics

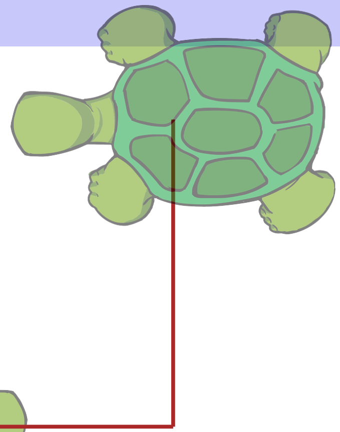
Turtle with position and direction.



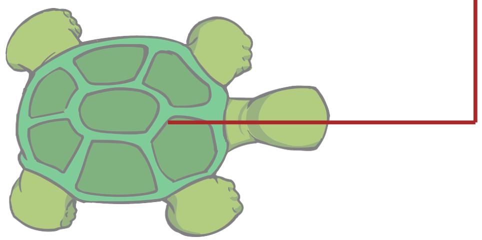
Turtle understands 3 commands:

F: one step forward ✓	+: turn by 90 degrees ✓	−: turn by −90 degrees ✓
		

Draw Words!



$w_1 = \mathrm{F} + \mathrm{F} + \checkmark$



lindenmayer.cpp: Main Program

Words $w_0, w_1, w_2, \ldots w_n \in \Sigma^*$: std::string

```
...
#include "turtle.h"
...
std::cout << "Number of iterations =? ";
unsigned int n;
std::cin >> n;

std::string w = "F";

for (unsigned int i = 0; i < n; ++i)
  w = next_word (w);

draw_word (w);
```

$w = w_0 = \mathrm{F}$

$w = w_i \to w = w_{i+1}$

draw $w = w_n$!

lindenmayer.cpp: next_word

```
// POST: replaces all symbols in word according to their
//       production and returns the result
std::string next_word (std::string word) {
  std::string next;
  for (unsigned int k = 0; k < word.length(); ++k)
    next += production (word[k]);
  return next;
}

// POST: returns the production of c
std::string production (char c) {
  switch (c) {
  case 'F': return "F+F+";
  default: return std::string (1, c); // trivial production c -> c
  }
}
```


lindenmayer.cpp: draw_word

```
// POST: draws the turtle graphic interpretation of word
void draw_word (std::string word)
{
  for (unsigned int k = 0; k < word.length(); ++k)
    switch (word[k]) {
    case 'F':
      turtle::forward();
     break;
    case '+':
      turtle::left(90);
      break;
    case '−':
      turtle::right(90);
    }
}
```

jump to the `case` that corresponds to `word[k]`.

forward! (function from our turtle library)

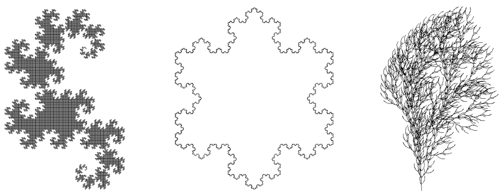
skip the remaining `cases`

turn by 90 degrees! (function from our turtle library)

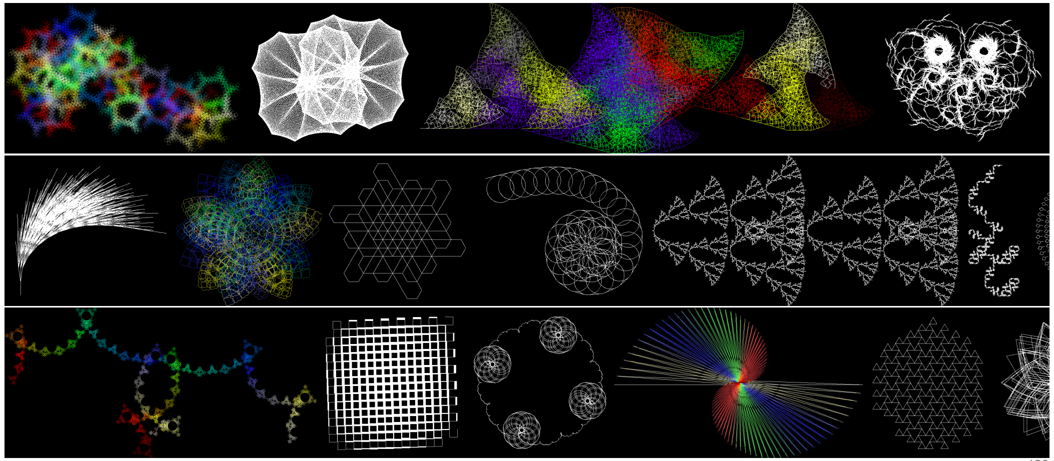
turn by -90 degrees (function from our turtle library)

L-Systems: Extensions

- Additional symbols without graphical interpretation (dragon.cpp)
- Arbitrary angles (snowflake.cpp)
- Saving and restoring the turtle state $\rightarrow$ plants (bush.cpp)



L-System-Challenge: `amazing.cpp!`



Multidimensional Arrays

- are arrays of arrays
- can be used to store *tables*, *matrices*, ...

`int a[2][3]`

a contains two elements and each of them is an array of length 3 with base type `int`

Multidimensional Arrays

In memory: flat

a[0][0]	a[0][1]	a[0][2]	a[1][0]	a[1][1]	a[1][2]

$\underbrace{\texttt{a[0][0]}\ \texttt{a[0][1]}\ \texttt{a[0][2]}}_{\texttt{a[0]}}\ \underbrace{\texttt{a[1][0]}\ \texttt{a[1][1]}\ \texttt{a[1][2]}}_{\texttt{a[1]}}$

in our head: matrix

columns →

rows ↓	0	1	2
0	a[0][0]	a[0][1]	a[0][2]
1	a[1][0]	a[1][1]	a[1][2]

Multidimensional Arrays

- are arrays of arrays of arrays ....

T a[expr$_1$] ... [expr$_k$]

constant expressions

a has *expr*$_1$ elements and each of them is an array with *expr*$_2$ elements each of which is an array of *expr*$_3$ elements and ...

Multidimensional Arrays

Initialization

```
int a[][3] =
    {
        {2,4,6},{1,3,5}
    }
```

First dimension can be omitted

2	4	6	1	3	5

Vectors of Vectors

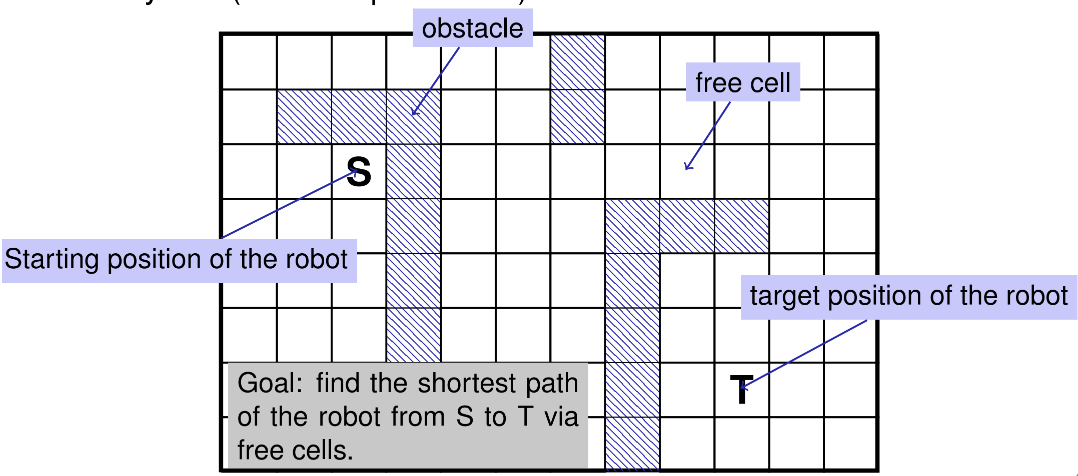
- How do we get multidimensional arrays with variable dimensions?
- Solution: vectors of vectors

Example: vector of length n of vectors with length m:

```
std::vector<std::vector<int> > a (n,
                    std::vector<int>(m));
```

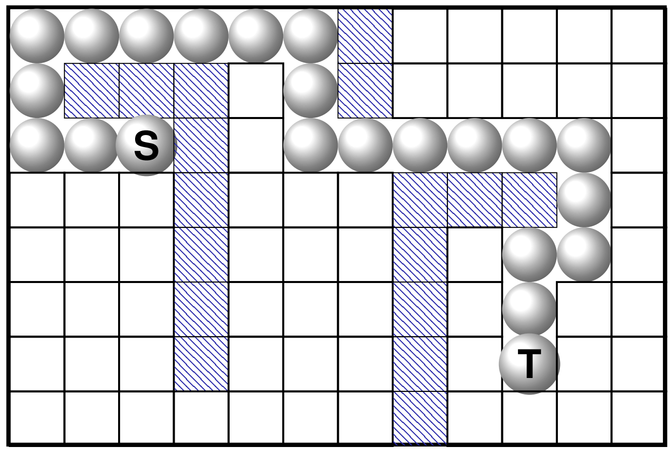

Application: Shortest Paths

Factory hall ($n \times m$ square cells)



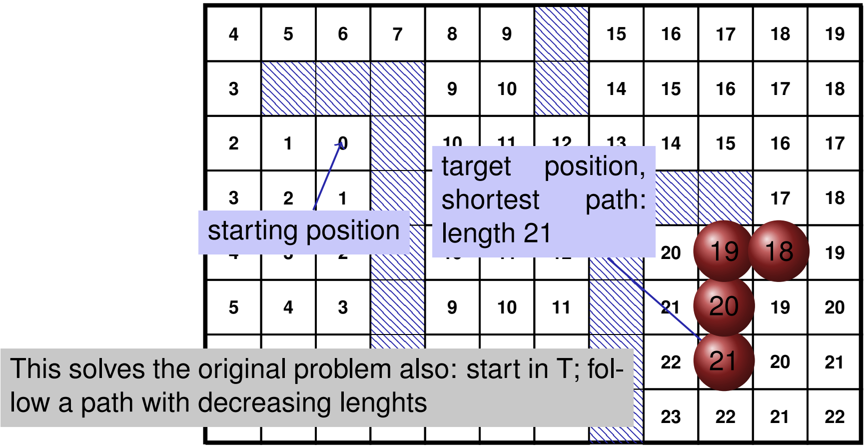
Application: shortest paths

Solution



This problem appears to be different

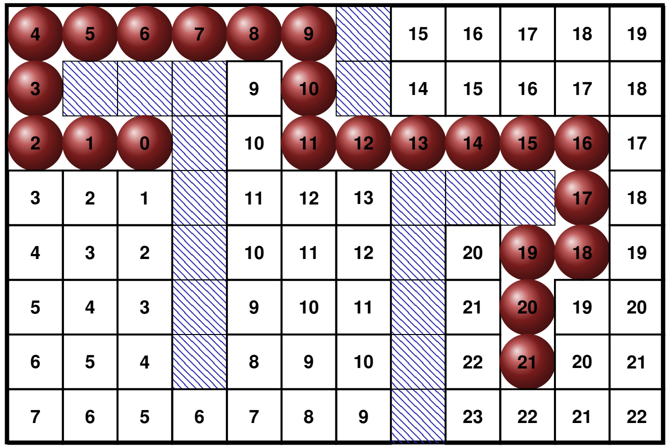
Find the *lengths* of the shortest paths to *all* possible targets.



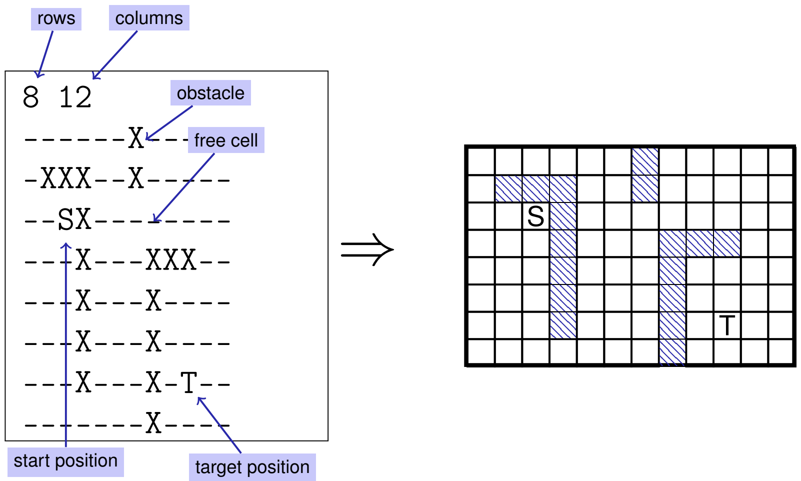
This solves the original problem also: start in T; follow a path with decreasing lenghts

This problem appears to be different

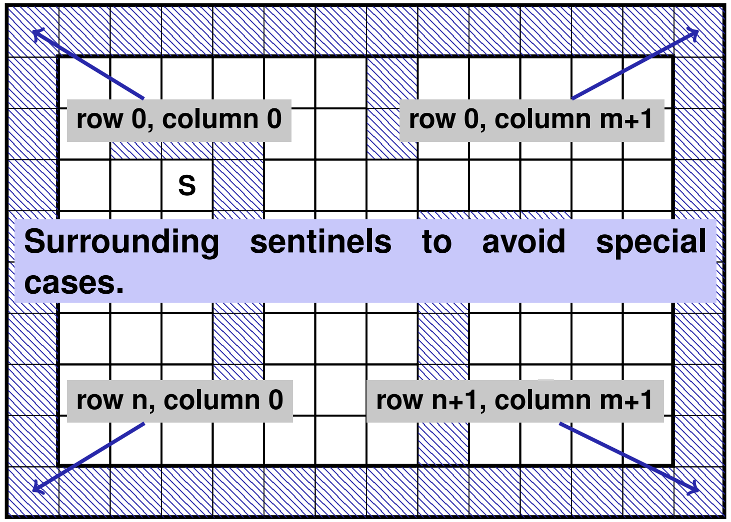
Find the *lengths* of the shortest paths to *all* possible targets.



Preparation: Input Format

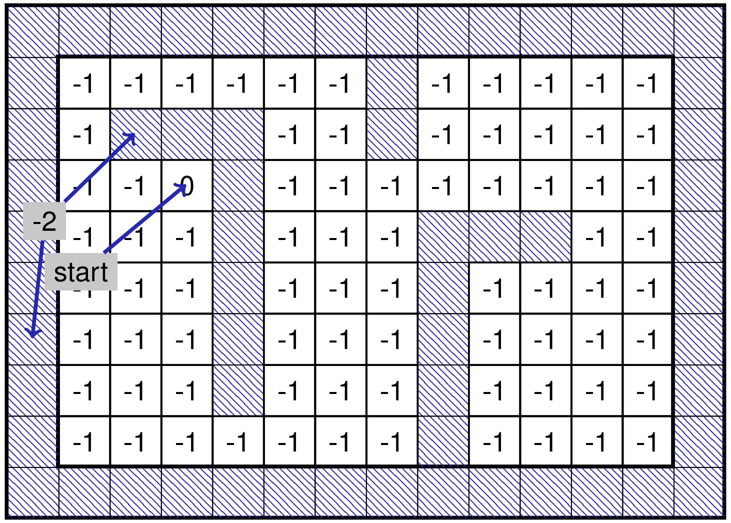


Preparation: Sentinels



Surrounding sentinels to avoid special cases.

Preparation: Initial Marking



The Shortest Path Program

- Read in dimensions and provide a two dimensional array for the path lengths

```
#include<iostream>
#include<vector>

int main()
{
  // read floor dimensions
  int n; std::cin >> n; // number of rows
  int m; std::cin >> m; // number of columns

  // define a two-dimensional
  // array of dimensions
  // (n+2) x (m+2) to hold the floor plus extra walls around
  std::vector<std::vector<int> > floor (n+2, std::vector<int>(m+2));
```

Sentinel

The Shortest Path Program

- Input the assignment of the hall and intialize the lengths

```
int tr = 0;
int tc = 0;
for (int r=1; r<n+1; ++r)
  for (int c=1; c<m+1; ++c) {
    char entry = '-';
    std::cin >> entry;
    if      (entry == 'S') floor[r][c] = 0;
    else if (entry == 'T') floor[tr = r][tc = c] = -1;
    else if (entry == 'X') floor[r][c] = -2;
    else if (entry == '-') floor[r][c] = -1;
  }
```


Das Kürzeste-Wege-Programm

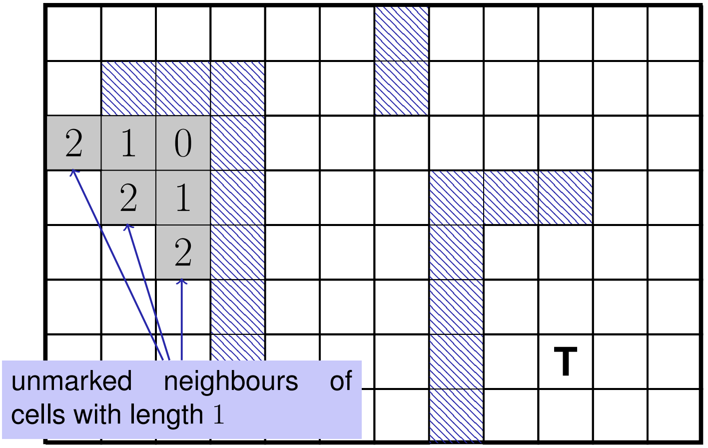
- Add the surrounding walls

```
for (int r=0; r<n+2; ++r)
  floor[r][0] = floor[r][m+1] = -2;

for (int c=0; c<m+2; ++c)
  floor[0][c] = floor[n+1][c] = -2;
```

Mark all Cells with their Path Lengths

Step 2: all cells with path length 2



Main Loop

Find and mark all cells with path lengths $i = 1, 2, 3...$

```
for (int i=1;; ++i) {
  bool progress = false;
  for (int r=1; r<n+1; ++r)
     for (int c=1; c<m+1; ++c) {
      if (floor[r][c] != −1) continue;
      if (floor[r−1][c] == i−1 || floor[r+1][c] == i−1 ||
          floor[r][c−1] == i−1 || floor[r][c+1] == i−1 ) {
        floor[r][c] = i; // label cell with i
        progress = true;
      }
    }
  if (!progress) break;
}
```


The Shortest Paths Program

Mark the shortest path by walking backwards from target to start.

```
int r = tr; int c = tc;
while (floor[r][c] > 0) {
  const int d = floor[r][c] − 1;
  floor[r][c] = −3;
  if      (floor[r−1][c] == d) −−r;
  else if (floor[r+1][c] == d) ++r;
  else if (floor[r][c−1] == d) −−c;
  else ++c; // (floor[r][c+1] == d)
}
```


Finish

-3	-3	-3	-3	-3	-3		15	16	17	18	19
-3				9	-3		14	15	16	17	18
-3	-3	0		10	-3	-3	-3	-3	-3	-3	17
3	2	1		11	12	13				-3	18
4	3	2		10	11	12		20	-3	-3	19
5	4	3		9	10	11		21	-3	19	20
6	5	4		8	9	10		22	-3	20	21
7	6	5	6	7	8	9		23	22	21	22

The Shortest Path Program: output

Output

```
for (int r=1; r<n+1; ++r) {
  for (int c=1; c<m+1; ++c)
    if (floor[r][c] == 0)
        std::cout << 'S';
    else if (r == tr && c == tc)
        std::cout << 'T';
    else if (floor[r][c] == -3)
        std::cout << 'o';
    else if (floor[r][c] == -2)
        std::cout << 'X';
    else
        std::cout << '-';
  std::cout << "\n";
}
```

$\Rightarrow$

```
ooooooX-----
oXXX-oX-----
ooSX-oooooo-
---X---XXXo-
---X---X-oo-
---X---X-o--
---X---X-T--
-------X----
```


The Shortest Paths Program

- Algorithm: *Breadth First Search*
- The program can become pretty slow because for each i all cells are traversed
- Improvement: for marking with i, traverse only the neighbours of the cells marked with $i - 1$.

Arrays as Function Arguments

Arrays can also be passed as *reference* arguments to a function. (here: const because v is read-only)

```
void print_vector(const int (&v)[3]) {
  for (int i = 0; i<3 ; ++i) {
    std::cout << v[i] << " ";
  }
}
```


Arrays as Function Argumenbts

This also works for multidimensional arrays.

```
void print_matrix(const int (&m)[3][3]) {
  for (int i = 0; i<3 ; ++i) {
    print_vector (m[i]);
    std::cout << "\n";
  }
}
```

Vectors as Function Arguments

Vectors can be passed *by value* or by *reference*

```
void print_vector(const std::vector<int>& v) {
  for (int i = 0; i<v.size() ; ++i) {
    std::cout << v[i] << " ";
  }
}
```

Here: *call by reference* is more efficient because the vector could be very long

Vectors as Function Arguments

This also works for multidimensional vectors.

```
void print_matrix(const std::vector<std::vector<int> >& m) {
  for (int i = 0; i<m.size() ; ++i) {
    print_vector (m[i]);
    std::cout << "\n";
  }
}
```


13. Pointers, Algorithms, Iterators and Containers I

Pointers, Address operator, Dereference operator, Array-to-Pointer Conversion

Strange Things…

```
#include<iostream>
#include<algorithm>

int main(){
  int a[] = {3, 2, 1, 5, 4, 6, 7};

  // output the smallest element of a
  std::cout << *std::min_element (a, a + 7);

  return 0;  ???                    ???
}
```

We have to undestand *pointers* first!

References: Where is Anakin?

“Search for Vader, and Anakin find you will”

```
int anakin_skywalker = 9;
int& darth_vader = anakin_skywalker;
darth_vader = 22;

// anakin_skywalker = 22
```

Pointers: Where is Anakin?

“Anakins address is `0x7fff6bdd1b54`.”

```
int anakin_skywalker = 9;
int* here = &anakin_skywalker;
std::cout << here; // Address
*here =  22;

// anakin_skywalker = 22
```

Swap with Pointers

```
void swap(int* x, int* y){
  int t = *x;
  *x = *y;
  *y = t;
}

...
int a = 2;
int b = 1;
swap(&a, &b);
std::cout << "a= " << a << "\n"; // 1
std::cout << "b = " << b << "\n"; // 2
```


Pointer Types

`T*` Pointer type to base type `T`.

An expression of type `T*` is called *pointer* (to `T`).

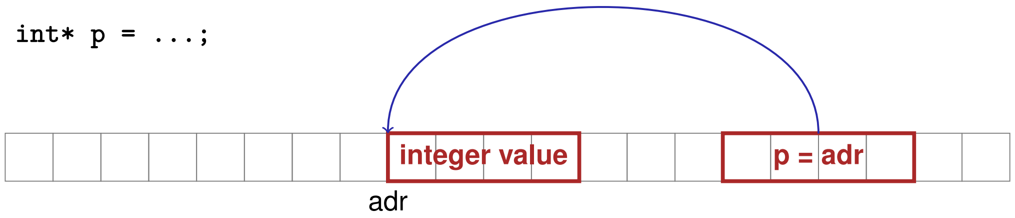
Pointer Types

Value of a pointer to `T` is the address of an object of type `T`.

Beispiele

`int* p;` Variable `p` is pointer to an `int`.
`float* q;` Variable `q` is pointer to a `float`.

```
int* p = ...;
```



Address Operator

The expression

L-value of type `T`
↓
& lval

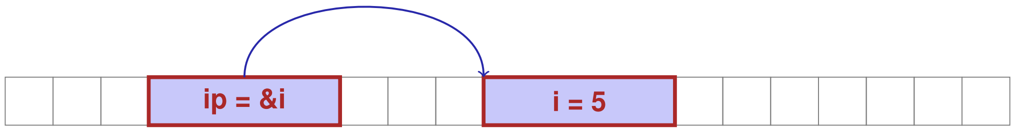
provides, as R-value, a *pointer* of type *T** to an object at the address of *lval*

The operator *&* is called Address-Operator.

Address Operator

Example

```
int i = 5;
int* ip = &i;  // ip initialized
               // with address of i.
```



Dereference Operator

The expression

R-value of type `T*`
↓
∗rval

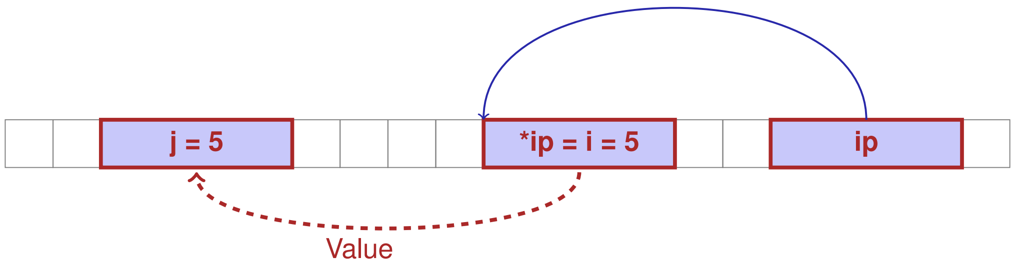
returns as L-value the *value* of the object at the address represented by *rval*.

The operator ∗ is called Derecerence Operator.

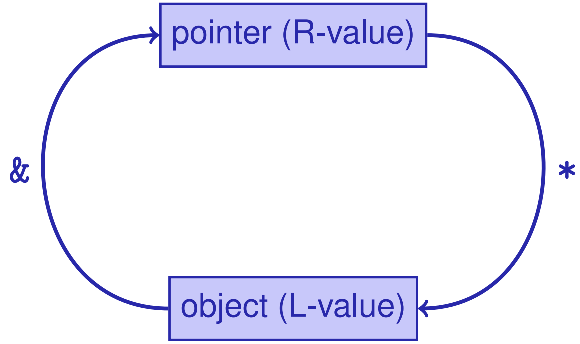
Dereference Operator

Beispiel

```
int i = 5;
int* ip = &i;   // ip initialized
                // with address of i.
int j = *ip;    // j == 5
```



Address and Dereference Operators



Pointer Types

Do not point with a `double*` to an `int`!

Examples

`int* i = ...;`   // at address `i` “lives” an `int`...
`double* j = i;`   //...and at `j` lives a `double`: error!

Mnenmonic Trick

The declaration

`T* p;`   `p` is of the type “pointer to `T`”

can be read as

`T *p;`   `*p` is of type `T`

Although this is legal, we do not write it like this!

Pointer Arithemtics: Pointer plus `int`

- *ptr*: Pointer to element $a[k]$ of the array a with length n
- Value of *expr*: integer i with $0 \leq k + i \leq n$

ptr + expr

is a pointer to $a[k + i]$.

For $k + i = n$ we get a *past-the-end*-pointer that must not be dereferenced.

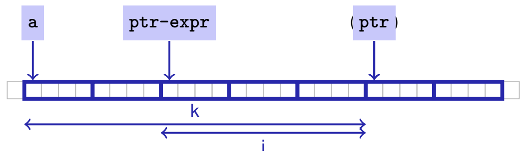
Pointer Arithemtics: Pointer minus `int`

- If *ptr* is a pointer to the element with index k in an array a with length n
- and the value of *expr* is an integer i, $0 \leq k - i \leq n$,

then the expression

ptr - expr

provides a pointer to an element of a with index $k - i$.



Conversion Array ⇒ Pointer

How do we get a pointer to the first element of an array?

- Static array of type $T[\mathrm{n}]$ is convertible to $T*$

Example

```
int a[5];
int* begin = a; // begin points to a[0]
```

- Length information is lost („arrays are primitive")

Iteration over an Array of Pointers

Example

```
int a[5] = {3, 4, 6, 1, 2};
for (int* p = a; p < a+5; ++p)
   std::cout << *p << ' '; // 3 4 6 1 2
```

- `a+5` is a pointer behind the end of the array (past-the-end) that must not be dereferenced.
- The pointer comparison (`p < a+5`) refers to the order of the two addresses in memory.