18. Classes

Classes, Member Functions, Constructors, Stack, Linked List, Dynamic Memory, Copy-Constructor, Assignment Operator, Concept Dynamic Datatype

Encapsulation: public / private

```
class rational {
  int n;
  int d; // INV: d != 0
};
```

Good news: `r.d = 0` cannot happen any more by accident.

Bad news: the customer cannot do anything any more . . .

. . . and we can't, either. (no `operator+`,. . .)

Application Code

```
rational r;
r.n = 1;      // error: n is private
r.d = 2;      // error: d is private
int i = r.n; // error: n is private
```


Member Functions: Declaration

```
class rational {
public:
  // POST: return value is the numerator of *this
  int numerator () const {
    return n;
  }
  // POST: return value is the denominator of *this
  int denominator () const {
    return d;
  }
private:
  int n;
  int d; // INV: d!= 0
};
```

public area

member function

member functions have access to private data

the scope of members in a class is the whole class, independent of the declaration order

Member Functions: Call

```
// Definition des Typs
class rational {
    ...
};
...
// Variable des Typs
rational r;

int n = r.numerator();    // Zaehler
int d = r.denominator(); // Nenner
```

member access

Member Functions: Definition

```
// POST: returns  numerator of *this
int numerator ()  const
{
  return n;
}
```

- A member function is called for an expression of the class. in the function, `*this` is the name of this implicit argument. `this` itself is a pointer to it.
- const refers to `*this`, i.e., it promises that the value associated with the implicit argument cannot be changed
- `n` is the shortcut in the member function for `(*this).n`

Comparison

It would look like this...

```
class rational {
    int n;
    ...

    int numerator () const
    {
        return (*this).n;
    }
};

rational r;
...
std::cout << r.numerator();
```

... without member functions

```
struct bruch {
    int n;
    ...
};

int numerator (const bruch∗ dieser)
{
    return (∗dieser).n;
}

bruch r;
..
std::cout << numerator(&r);
```


Member-Definition: In-Class vs. Out-of-Class

```
class rational {
    int n;
    ...

    int numerator () const
    {
        return n;
    }
    ....
};
```

- No separation between declaration and definition (bad for libraries)

```
class rational {
    int n;
    ...

    int numerator () const;
    ...
};

int rational::numerator () const
{
  return n;
}
```

- This also works.

Constructors

- are special member functions of a class that are named like the class
- can be overloaded like functions, i.e. can occur multiple times with varying *signature*
- are called like a function when a variable is declared. The compiler chooses the “closest” matching function.
- if there is no matching constructor, the compiler emits an *error message*.

Initialisation? Constructors!

```
class rational
{
public:
    rational (int num, int den)
        : n (num), d (den)←—— Initialization of the member variables
    {
        assert (den != 0); ←—— function body.
    }
...
};
...
rational r (2,3); // r = 2/3
```


Constructors: Call

- directly

```
rational r (1,2); // initialisiert r mit 1/2
```

- indirectly (copy)

```
rational r = rational (1,2);
```


Initialisation "rational = int"?

```
class rational
{
public:
    rational (int num)
       : n (num), d (1)
    {}  ←—— empty function body
...
};
...
rational r (2);    // explicit initialization with 2
rational s = 2;    // implicit conversion
```


User Defined Conversions

are defined via constructors with exactly *one* argument

```
rational (int num) ←——
    : n (num), d (1)
  {}
```

User defined conversion from `int` to `rational`. values of type `int` can now be converted to `rational`.

```
rational r = 2; // implizite Konversion
```

The Default Constructor

```
class rational
{
public:                    empty list of arguments
    ...
    rational ()<-
      : n (0), d (1)
    {}
...
};
...
rational r;    // r = 0
```

⇒ There are no uninitiatlized variables of type rational any more!

The Default Constructor

- is automatically called for declarations of the form **`rational r;`**
- is the unique constructor with empty argmument list (if existing)
- must exist, if **`rational r;`** is meant to compile
- if in a struct there are no constructors at all, the default constructor is automatically generated

RAT PACK® Reloaded ...

Customer's program now looks like this:

```
// POST: double approximation of r
double to_double (const rational r)
{
  double result = r.numerator();
  return result / r.denominator();
}
```

- We can adapt the member functions together with the representation ✓

RAT PACK® Reloaded ...

before

```
class rational {
...
private:
  int n;
  int d;
};
```

```
int numerator () const
{
  return n;
}
```

after

```
class rational {
...
private:
  unsigned int n;
  unsigned int d;
  bool is_positive;
};
```

```
int numerator () const{
  if (is_positive)
    return n;
  else {
    int result = n;
    return -result;
  }
}
```

RAT PACK® Reloaded ?

```
class rational {
...
private:
  unsigned int n;
  unsigned int d;
  bool is_positive;
};
```

```
int numerator () const
{
  if (is_positive)
    return n;
  else {
    int result = n;
    return −result;
  }
}
```

- value range of nominator and denominator like before
- possible overflow in addition

Encapsulation still Incompleete

Customer's point of view (rational.h):

```
class rational {
public:
   // POST: returns numerator of *this
   int numerator () const;
   ...
private:
  // none of my business
};
```

- We determined denominator and nominator type to be `int`
- Solution: encapsulate not only data but alsoe types.

Fix: "our" type `rational::integer`

Customer's point of view (rational.h):

```
public:
   typedef int integer; // might change
   // POST: returns numerator of *this
   integer numerator () const;
```

- We provide an additional type!
- Determine only Functionality, e.g:
  - implicit conversion `int` → `rational::integer`
  - function `double to_double (rational::integer)`

RAT PACK® Revolutions

Finally, a customer program that remains stable

```
// POST: double approximation of r
double to_double (const rational r)
{
  rational::integer n = r.numerator();
  rational::integer d = r.denominator();
  return to_double (n) / to_double (d);
}
```

Separate Declaration and Definition

```
class rational {
public:
   rational (int num, int denum);
   typedef int integer;
   integer numerator () const;
   ...
private:
 ...
};
rational::rational (int num, int den):
    n (num), d (den) {}
rational::integer rational::numerator () const
{
    return n;
}
```

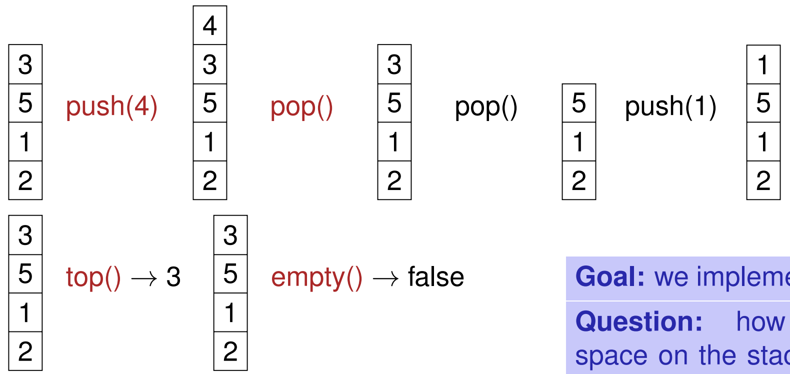
rational.h

rational.cpp

class name :: member name

Motivation: Stack

Motivation: Stack (push, pop, top, empty)



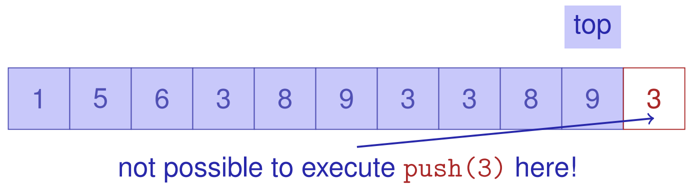
Goal: we implement a stack class

Question: how do we create space on the stack when push is called?

We Need a new Kind of Container

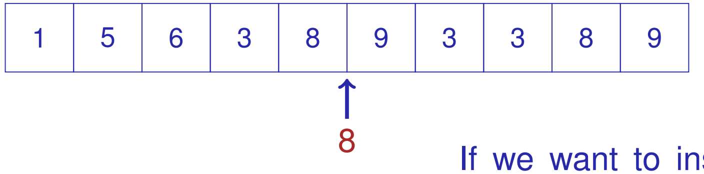
Our main container: Array (`T[]`)

- Contiguous area of memory, random access (to ith element)
- Simulation of a stack with an array?
- No, at some point the array will become "full".



Arrays are no all-rounders…

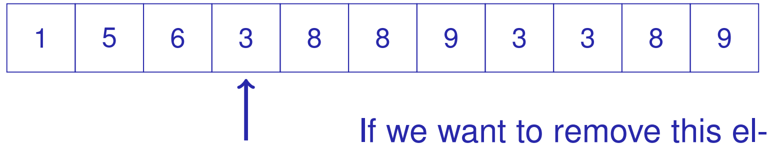
- It is expensive to insert or delete elements “in the middle ”.



If we want to insert, we have to move everything to the right (if there is space at all!)

Arrays are no all-rounders…

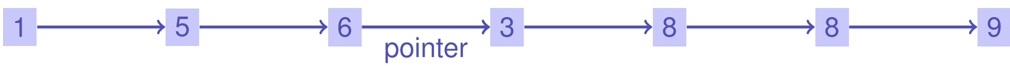
- It is expensive to insert or delete elements “in the middle ”.



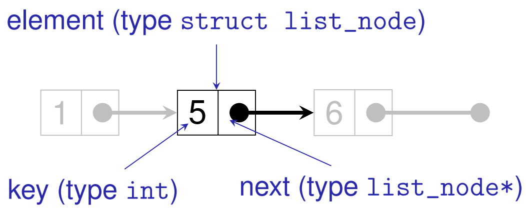
If we want to remove this element, we have to move everything to the right of it.

The new Container: Linked List

- *No* contiguous area of memory and *no* random access
- Each element “knows” its successor
- Insertion and deletion of arbitrary elements is simple, *even at the beginning of the list*
- ⇒ A stack can be implemented as linked list

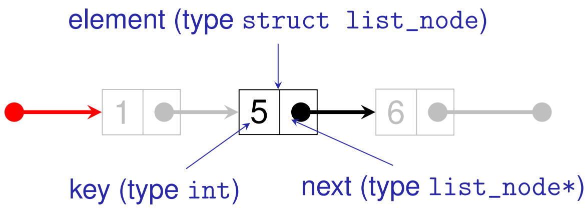


Linked List: Zoom




```
struct list_node {
  int           key;
  list_node*    next;
  // constructor
  list_node (int k, list_node* n)
    : key (k), next (n) {}
};
```

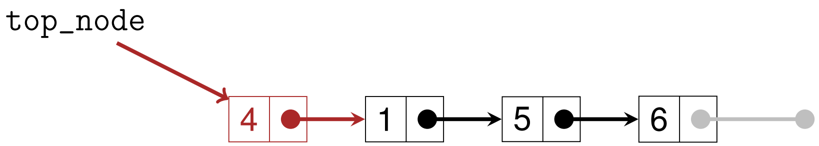
Stack = Pointer to the Top Element




```
class stack {
public:
   void push (int value) {...}
   ...
private:
   list_node* top_node;
};
```


Sneak Preview: `push(4)`

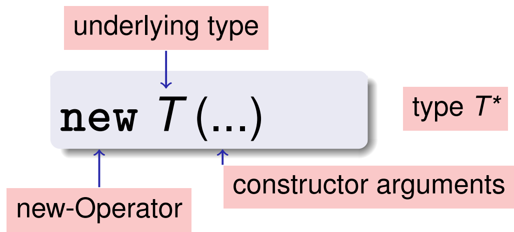
```
void push (int value)
{
  top_node = new list_node (value, top_node);
}
```



Dynamic Memory

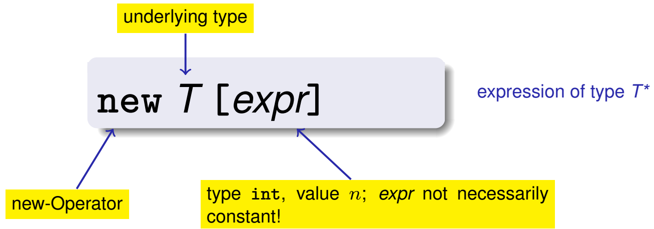
- For dynamic data structures like lists we need *dynamic memory*
- Up to now we had to fix the memory sizes of variable at *compile time*
- Pointers allow to request memory at *runtime*
- Dynamic memory management in C++ with operators `new` and `delete`

The `new` Expression



- **Effect:** new object of type *T* is allocated in memory . . .
- . . . and initialized by means of the matching constructor.
- **Value:** address of the new object

`new` for Arrays

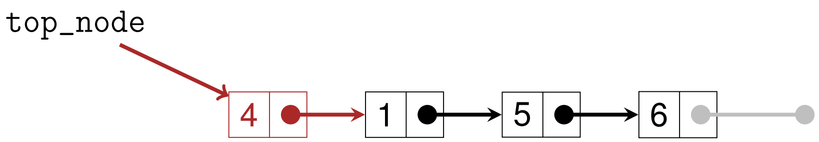


- memory for an array with length n and underlying type *T* is allocated
- Value of the expression is the address of the first element of the array

The `new` Expression push(4)

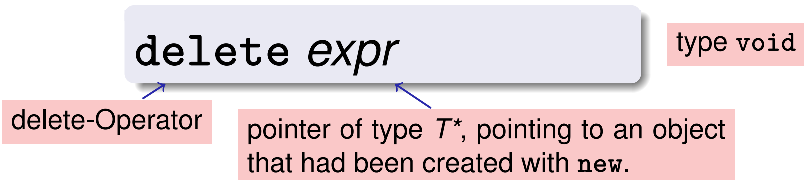
- **Effect:** new object of type *T* is allocated in memory ...
- ... and intialized by means of the matching constructor
- **Value:** address of the new object

```
top_node = new list_node (value, top_node);
```



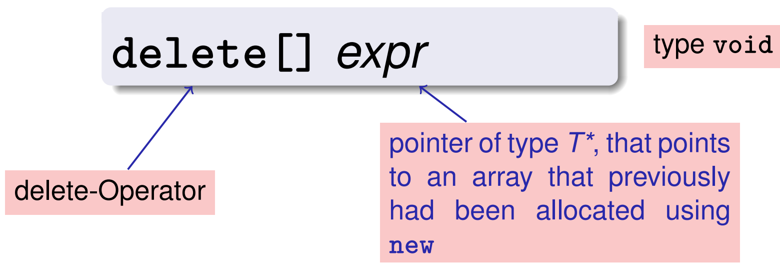
The `delete` Expression

Objects generated with `new` have *dynamic storage duration:* they “live” until they are explicitly *deleted*



- **Effect:** object is deleted and memory is released

`delete` for Arrays



- **Effect:** array is deleted and memory is released

Carefult with `new` and `delete`!

```
rational* t = new rational;
rational* s = t;
delete s;
int nominator = (*t).denominator();
```

- `rational* t = new rational;` ← memory for t is allocated
- `rational* s = t;` ← other pointers may also point to the same object
- `delete s;` ← ... and used for releaseing the object
- `int nominator = (*t).denominator();` ← error: memory already released!
- `(*t)`: Dereferencing of „dangling pointers"

- Pointer to released objects: *dangling pointers*
- Releasing an object more than once using `delete` is a similar severe error
- `delete` can be easily forgotten: consequence are *memory leaks*. Can lead to memory overflow in the long run.

Who is born must die. . .

Guideline "Dynamic Memory"

For each `new` there is a matching `delete`!

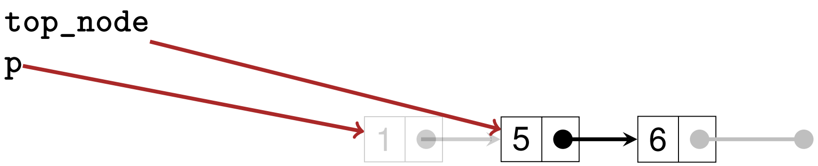
Non-compliance leads to memory leaks

- old objects that occupy memory. . .
- . . . until it is full (heap overflow)

Stack Continued: `pop()`

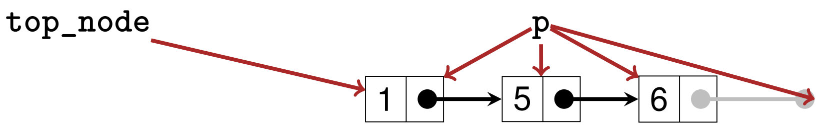
```
void pop()
{
    assert (!empty());
    list_node* p = top_node;
    top_node = top_node->next;
    delete p;
}
```

`top_node->next`: shortcut for `(*top_node).next`



Traverse the Stack `print()`

```
void print (std::ostream& o) const
{
  const list_node* p = top_node;
  while (p != 0) {
    o << p->key << " "; // 1 5 6
    p = p->next;
  }
}
```



Output Stack: operator<<

```
class stack {
public:
   void push (int value) {...}
   ...
   void print (std::ostream& o) const {...}
private:
   list_node* top_node;
};

// POST: s is written to o
std::ostream& operator<< (std::ostream& o, const stack& s)
{
   s.print (o);
   return o;
}
```


Empty Stack , empty(), top()

```
stack()       // default constructor
    : top_node (0)
{}

bool empty () const
{
  return top_node == 0;
}

int top () const
{
  assert (!empty());
  return top_node->key;
}
```


Stack Done? Obviously not...

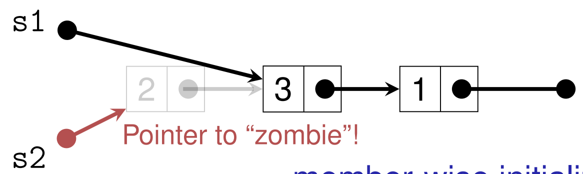
```
stack s1;
s1.push (1);
s1.push (3);
s1.push (2);
std::cout << s1 << "\n"; // 2 3 1

stack s2 = s1;
std::cout << s2 << "\n"; // 2 3 1

s1.pop ();
std::cout << s1 << "\n"; // 3 1

s2.pop (); // Oops, crash!
```


What has gone wrong?



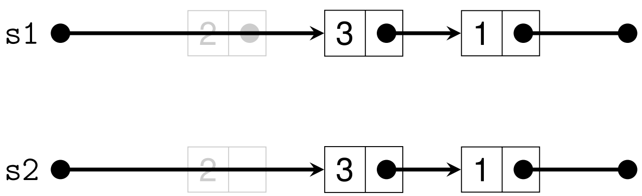
member-wise initialization: copies the `top_node` pointer only.

```
...
stack s2 = s1;
std::cout << s2 << "\n"; // 2 3 1

s1.pop ();
std::cout << s1 << "\n"; // 3 1

s2.pop ();  // Oops, crash!
```

We need a real copy




```
...
stack s2 = s1;
std::cout << s2 << "\n"; // 2 3 1

s1.pop ();
std::cout << s1 << "\n"; // 3 1

s2.pop ();  // ok
```


The Copy Constructor

- The copy constructor of a class *T* is the unique constructor with declaration

  T (`const` *T*& x);

- is automatically called when values of type *T* are initialized with values of type `T`

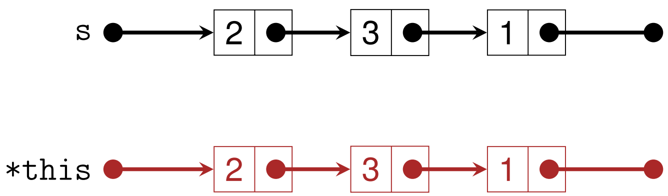
  `T x = t;`   (t of type T)
  `T x (t);`

- If there is no copy-constructor declared then it is generated automatically (and initializes member-wise – reason for the problem above

It works with a Copy Constructor

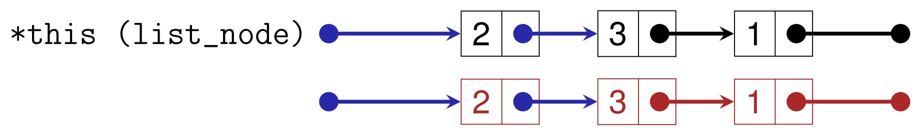
We use a copy function of the `list_node`:

```
// POST: *this is initialized with a copy of s
stack (const stack& s)
  : top_node (0)
{
  if (s.top_node != 0)
    top_node = s.top_node->copy();
}
```



The (Recursive) Copy Function of `list_node`

```
// POST: pointer to a copy of the list starting
//       at *this is returned
list_node* copy () const
{
  if (next != 0)
    return new list_node (key, next->copy());
  else
    return new list_node (key, 0);
}
```



Initialization ≠ Assignment!

```
stack s1;
s1.push (1);
s1.push (3);
s1.push (2);
std::cout << s1 << "\n"; // 2 3 1

stack s2;
s2 = s1; // Zuweisung

s1.pop ();
std::cout << s1 << "\n"; // 3 1
s2.pop (); // Oops, Crash!
```


The Assignment Operator

- Overloading **`operator=`** as a member function
- Like the copy-constructor without initializer, but additionally
  - Releasing memory for the “old” value
  - Check for self-assignment (`s1=s1`) that should not have an effect
- If there is no assignment operator declared it is automatically generated (and assigns member-wise – reason for the problem above

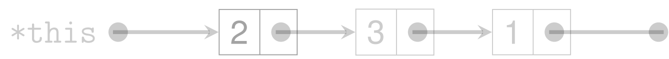
It works with an Assignment Operator!

Here a release function of the `list_node` is used:

```
// POST: *this (left operand) is getting a copy of s (right operand)
stack& operator= (const stack& s)
{
  if (top_node != s.top_node) { // keine Selbtszuweisung!
    if (top_node != 0) {
      top_node->clear(); // loesche Knoten in *this
      top_node = 0;
  }
    if (s.top_node != 0)
      top_node = s.top_node->copy(); // kopiere s nach *this
    }
  return *this; // Rueckgabe als L-Wert (Konvention)
}
```


The (recursive) release function of `list_node`

```
// POST: the list starting at *this is deleted
void clear ()
{
  if (next != 0)
    next->clear();
  delete this;
}
```



Zombie Elements

```
{
  stack s1; // local variable
  s1.push (1);
  s1.push (3);
  s1.push (2);
  std::cout << s1 << "\n"; // 2 3 1
}
// s1 has died (become invalid)...
```

- ... but the three elements of the stack `s1` continue to live (memory leak)!
- They should be released together with `s1`.

The Destructor

- The Destructor of class *T* is the unique member function with declaration

  ~*T* ( );
- is automatically called when the memory duration of a class object ends
- If no destructor is declared, it is automatically generated and calls the destructors for the member variables (pointers `top_node`, no effect – reason for zombie elements

Using a Destructor, it Works

```
// POST: the dynamic memory of *this is deleted
~stack()
{
  if (top_node != 0)
    top_node->clear();
}
```

- automatically deletes all stack elements when the stack is being released
- Now our stack class follows the guideline “dynamic memory”

Dynamic Datatype

- Type that manages dynamic memory (e.g. our class for a stack)
- Other Applications:
  - Lists (with insertion and deletion “in the middle”)
  - Trees (next week)
  - waiting queues
  - graphs
- Minimal Functionality:
  - Constructors
  - Destructor
  - Copy Constructor
  - Assignment Operator

  (Destructor, Copy Constructor, Assignment Operator:) Rule of Three: if a class defines at least one of them, it must define all three