23. Dynamic Datatypes and Memory Management

Problem

Last week: dynamic data type

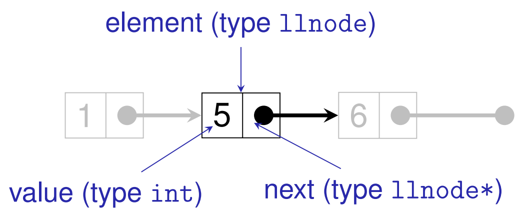
Have allocated dynamic memory, but not released it again. In particular: no functions to remove elements from `llvec`.

Today: correct memory management!

Goal: class stack with memory management

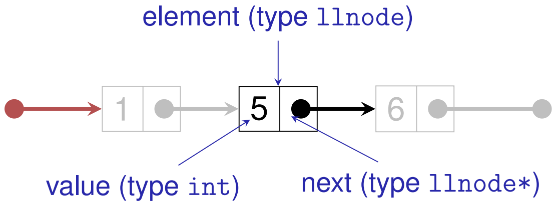
```
class stack{
public:
  // post: Push an element onto the stack
  void push(int value);
  // pre: non-empty stack
  // post: Delete top most element from the stack
  void pop();
  // pre: non-empty stack
  // post: return value of top most element
  int top() const;
  // post: return if stack is empty
  bool empty() const;
  // post: print out the stack
  void print(std::ostream& out) const;
...
```


Recall the Linked List



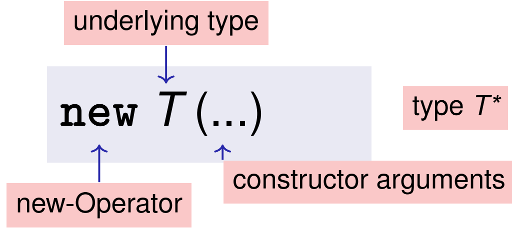

```
struct llnode {
  int value;
  llnode* next;
  // constructor
  llnode (int v, llnode* n) : value (v), next (n) {}
};
```

Stack = Pointer to the Top Element




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


Recall the `new` Expression

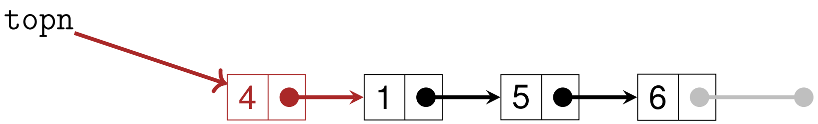


- **Effect:** new object of type *T* is allocated in memory . . .
- . . . and initialized by means of the matching constructor.
- **Value:** address of the new object

The `new` Expression `push(4)`

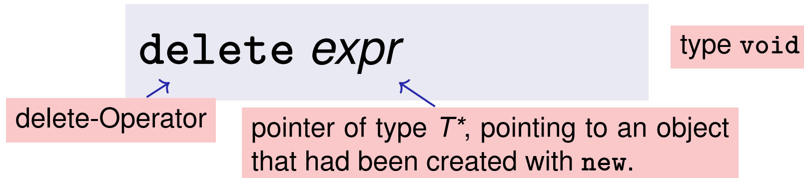
- **Effect:** new object of type *T* is allocated in memory . . .
- . . . and intialized by means of the matching constructor
- **Value:** address of the new object

```
void stack::push(int value){
  topn = new llnode (value, topn);
}
```



The `delete` Expression

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



- **Effect:** object is *deconstructed* (explanation below)
  ... and *memory is released*.

`delete` for Arrays

`delete[]` *expr*

type `void`

delete-Operator

pointer of type *T**, that points to an array that previously had been allocated using `new`

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

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)

Careful 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 point to the same object
- `delete s;` ← ... and used for releaseing the object
- `int nominator = (*t).denominator();` ← error: memory released!

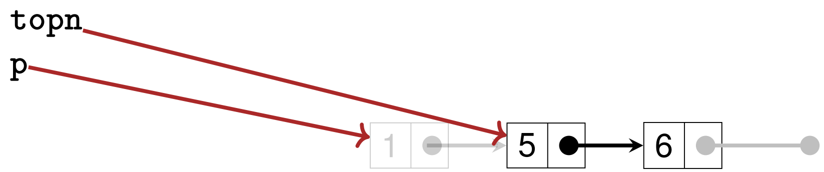
`(*t)`: Dereferencing of „dangling pointers"

- Pointer to released objects: *dangling pointers*
- Releasing an object more than once using `delete` is a similar severe error

Stack Continued: `pop()`

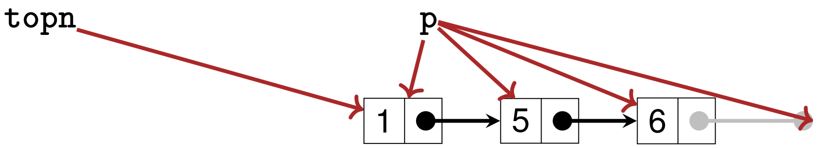
```
void stack::pop(){
    assert (!empty());
    llnode* p = topn;
    topn = topn->next;
    delete p;
}
```

`topn->next` — reminder: shortcut for `(*topn).next`



Print the Stack `print()`

```
void stack::print (std::ostream& out) const {
  for(const llnode* p = topn; p != nullptr; p = p->next)
    out << p->value << " "; // 1 5 6
}
```



Output Stack: `operator<<`

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

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


`empty()`, `top()`

```
bool stack::empty() const {
  return top == nullptr;
}

int stack::top() const {
  assert(!empty());
  return topn->value;
}
```


Empty Stack

```
class stack{
public:
  stack() : topn (nullptr) {} // default constructor

  void push(int value);
  void pop();
  void print(std::ostream& out) const;
  int top() const;
  bool empty() const;
private:
  llnode* topn;
}
```

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

  $\sim T\,(\,);$

- is automatically called when the memory duration of a class object ends – i.e. when `delete` is called on an object of type `T*` or when the enclosing scope of an object of type `T` ends.
- If no destructor is declared, it is automatically generated and calls the destructors for the member variables (pointers `topn`, no effect – reason for zombie elements

Using a Destructor, it Works

```
// POST: the dynamic memory of *this is deleted
stack::~stack(){
  while (topn != nullptr){
    llnode* t = topn;
    topn = t->next;
    delete t;
  }
}
```

- automatically deletes all stack elements when the stack is being released
- Now our stack class seems to follow the guideline “dynamic memory” (?)

Stack Done? Obviously not. . .

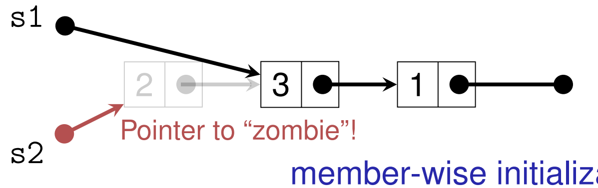
```
stack s1;
s1.push (1);
s1.push (3);
s1.push (2);
std::cout << s1 << "\n"; // 2 3 1

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 `topn` pointer only.

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

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

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


The actual problem

Already this goes wrong:

```
{
  stack s1;
  s1.push(1);
  stack s2 = s1;
}
```

When leaving the scope, both stacks are deconstructed. But both stacks try to delete the same data, because both stacks have *access to the same pointer*.

Possible solutions

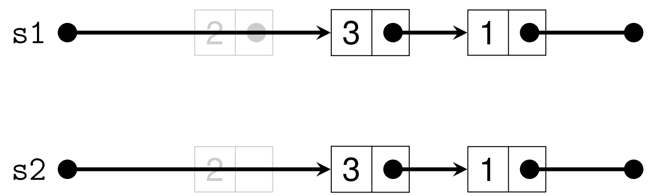
Smart-Pointers (we will not go into details here):

- Count the number of pointers referring to the same objects and delete only when that number goes down to 0 **`std::shared_pointer`**
- Make sure that not more than one pointer can point to an object: **`std::unique_pointer`**.

or:

- We make a real copy of all data – as discussed below.

We make 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);

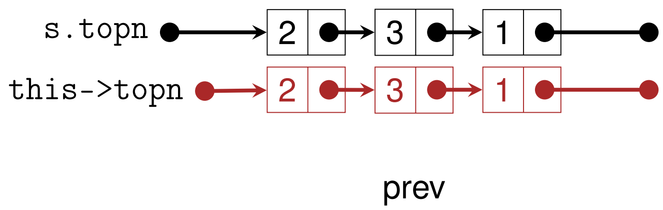
- is automatically called when values of type *T* are initialized with values of type `T`

  ```
  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

```
// POST: *this is initialized with a copy of s
stack::stack (const stack& s) : topn (nullptr) {
  if (s.topn == nullptr) return;
  topn = new llnode(s.topn->value, nullptr);
  llnode* prev = topn;
  for(llnode* n = s.topn->next; n != nullptr; n = n->next){
    llnode* copy = new llnode(n->value, nullptr);
    prev->next = copy;
    prev = copy;
  }
}
```



Aside: copy recursively

```
llnode* copy (node* that){
  if (that == nullptr) return nullptr;
  return new llnode(that->value, copy(that->next));
}
```

Elegant, isn't it? Why did we not do it like this?

Reason: linked lists can become very long. `copy` could then lead to stack overflow[7]. Stack memory is usually smaller than heap memory.

[7] not an overflow of the stack that we are implementing but the call stack

Initialization $\neq$ 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!

```
// POST: *this (left operand) becomes a
//           copy of s (right operand)
stack& stack::operator= (const stack& s){
  if (topn != s.topn){ // no self-assignment
    stack copy = s; // Copy Construction
    std::swap(topn, copy.topn); // now copy has the garbag
  } // copy is cleaned up -> deconstruction
  return *this; // return as L-Value (convention)
}
```

Cooool trick! ☺

Done

```
class stack{
public:
  stack(); // constructor
  ~stack(); // destructor
  stack(const stack& s); // copy constructor
  stack& operator=(const stack& s); // assignment operator

  void push(int value);
  void pop();
  int top() const;
  bool empty() const;
  void print(std::ostream& out) const;
private:
  llnode* topn;
}
```

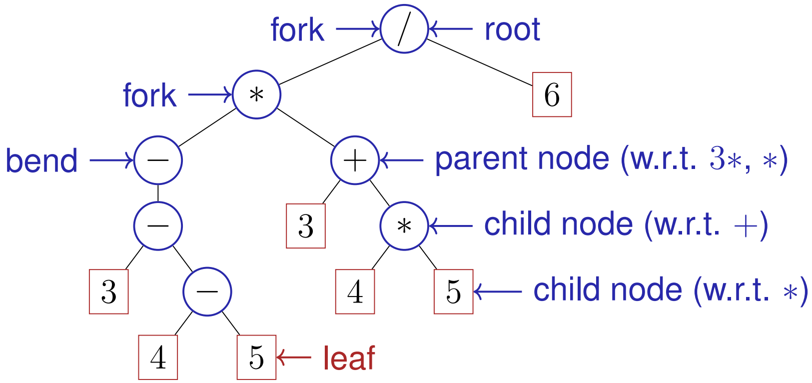

Dynamic Datatype

- Type that manages dynamic memory (e.g. our class for a stack)
- Minimal Functionality:
  - Constructors
  - Destructor
  - Copy Constructor
  - Assignment Operator

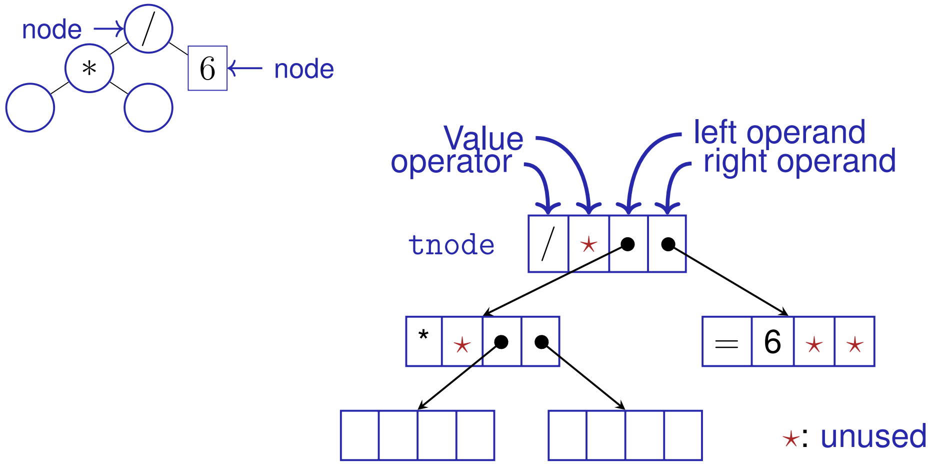
} *Rule of Three:* if a class defines at least one of them, it must define all three

(Expression) Trees

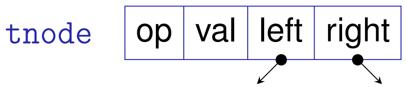
`-(3-(4-5))*(3+4*5)/6`



Nodes: Forks, Bends or Leaves



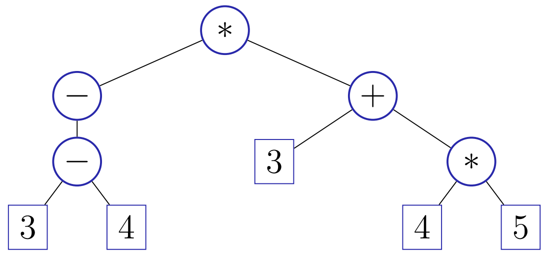
Nodes (`struct tnode`)




```
struct tnode {
  char op; // leaf node: op is '='
           // internal node: op is '+', '−', '∗' or '/'
  double val;
  tnode∗ left; // == nullptr for unary minus
  tnode∗ right;

  tnode(char o, double v, tnode∗ l, tnode∗ r)
    : op(o), val(v), left(l), right(r) {}
};
```

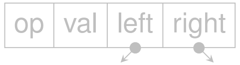

Size = Count Nodes in Subtrees



- Size of a leave: 1
- Size of other nodes: 1 + sum of child nodes' size
- E.g. size of the "+"-node is 5

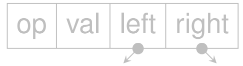
Count Nodes in Subtrees

```
// POST: returns the size (number of nodes) of
//       the subtree with root n
int size (const tnode* n) {
  if (n){ // shortcut for n != nullptr
    return size(n->left) + size(n->right) + 1;
  }
  return 0;
}
```



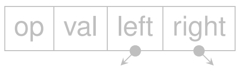
Evaluate Subtrees

```
// POST: evaluates the subtree with root n
double eval(const tnode* n){
  assert(n);
  if (n->op == '=') return n->val; ← leaf...
  double l = 0;                      ...or fork:
  if (n->left) l = eval(n->left); ← op unary, or left branch
  double r = eval(n->right);←———— right branch
  switch(n->op){
    case '+': return l+r;
    case '-': return l-r;
    case '*': return l*r;
    case '/': return l/r;
    default: return 0;
  }
}
```



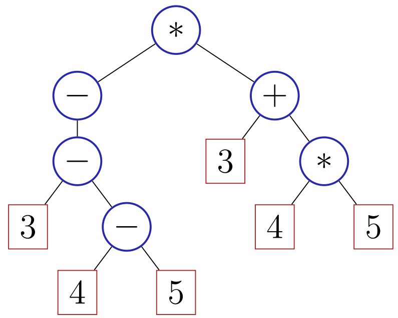
Cloning Subtrees

```
// POST: a copy of the subtree with root n is made
//       and a pointer to its root node is returned
tnode* copy (const tnode* n) {
  if (n == nullptr)
    return nullptr;
  return new tnode (n->op, n->val, copy(n->left), copy(n->right));
}
```



Felling Subtrees

```
// POST: all nodes in the subtree with root n are deleted
void clear(tnode* n) {
  if(n){
    clear(n->left);
    clear(n->right);
    delete n;
  }
}
```



Using Expression Subtrees

```
// Construct a tree for 1 − (−(3 + 7))
tnode∗ n1 = new tnode('=', 3, nullptr, nullptr);
tnode∗ n2 = new tnode('=', 7, nullptr, nullptr);
tnode∗ n3 = new tnode('+', 0, n1, n2);
tnode∗ n4 = new tnode('−', 0, nullptr, n3);
tnode∗ n5 = new tnode('=', 1, nullptr, nullptr);
tnode∗ root = new tnode('−', 0, n5, n4);

// Evaluate the overall tree
std::cout << "1 − (−(3 + 7)) = " << eval(root) << '\n';

// Evaluate a subtree
std::cout << "3 + 7 = " << eval(n3) << '\n';

clear(root); // free memory
```

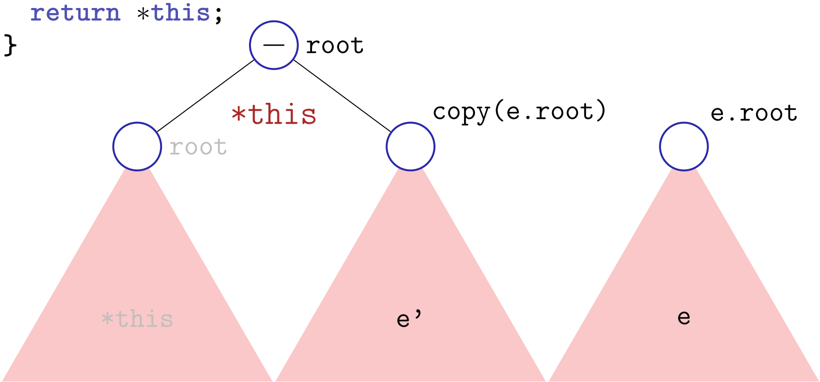

Planting Trees

```
class texpression {
public:
    texpression (double d)
        : root (new tnode ('=', d, 0, 0)) {}
    ...
private:
    tnode∗ root;
};
```

creates a tree with one leaf

Letting Trees Grow

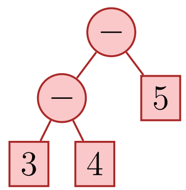
```
texpression& texpression::operator−= (const texpression& e)
{
  assert (e.root);
  root = new tnode ('−', 0, root, copy(e.root));
  return ∗this;
}
```



Raising Trees

```
texpression operator− (const texpression& l,
                       const texpression& r){
    texpression result = l;
    return result −= r;
}

texpression a = 3;
texpression b = 4;
texpression c = 5;
texpression d = a−b−c;
```



Rule of three: Clone, reproduce and cut trees

```
texpression::~texpression(){
  clear(root);
}

texpresssion::texpression (const texpression& e)
     : root(copy(e.root)) { }

texpression& texpression::operator=(const texpression& e){
  if (root != e.root){
    texpression cp = e;
    std::swap(cp.root, root);
  }
  return *this;
}
```


Concluded

```
class texpression{
public:
  texpression (double d); // constructor
  ~texpression(); // destructor
  texpression (const texpression& e); // copy constructor
  texpression& operator=(const texpression& e); // assignment op
  texpression operator−();
  texpression& operator−=(const texpression& e);
  texpression& operator+=(const texpression& e);
  texpression& operator∗=(const texpression& e);
  texpression& operator/=(const texpression& e);
  double evaluate();
private:
 tnode∗ root;
};
```


From values to trees!

```
using number_type = texpression ;

// term = factor { "∗" factor | "/" factor }
number_type term (std::istream& is){
  number_type value = factor (is);
  while (true) {
    if (consume (is, '∗'))
      value ∗= factor (is);
    else if (consume (is, '/'))
      value /= factor (is);
   else
      return value;
  }
}
```

double_calculator.cpp
(expression value)
→
texpression_calculator.cpp
(expression tree)

Concluding Remark

- In this lecture, we have intentionally refrained from implementing member functions in the node classes of the list or tree.[8]
- When there is inheritace and polymorphism used, the implementation of the functionality such as evaluate, print, clear (etc:.) is better implemented in member functions.
- In any case it is not a good idea to implement the memory management of the composite data strcuture list or tree within the nodes.

[8] Parts of the implementations are even simpler (because the case `n==nullptr` can be caught more easily