Lecture 1 – Syntax and Semantics

SWS128: Software Analysis

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2026 Fall

Recall

- Testing shows the presence of faults, not their absence.
- An **analyzer** decides whether a program satisfies a property — by running it (dynamic) or without (static).
- No analyzer is sound, complete, and terminating at once (Rice's theorem). Every analysis gives something up.

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- Today: before analyzing programs, we must say **precisely** what a program is and what it does.

Contents

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Concrete and Abstract Syntax

- **Concrete syntax**: the characters a programmer types.
  - `x = (1 + 2) * y`
  - Parentheses, whitespace, keywords, operator precedence.

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PLRG

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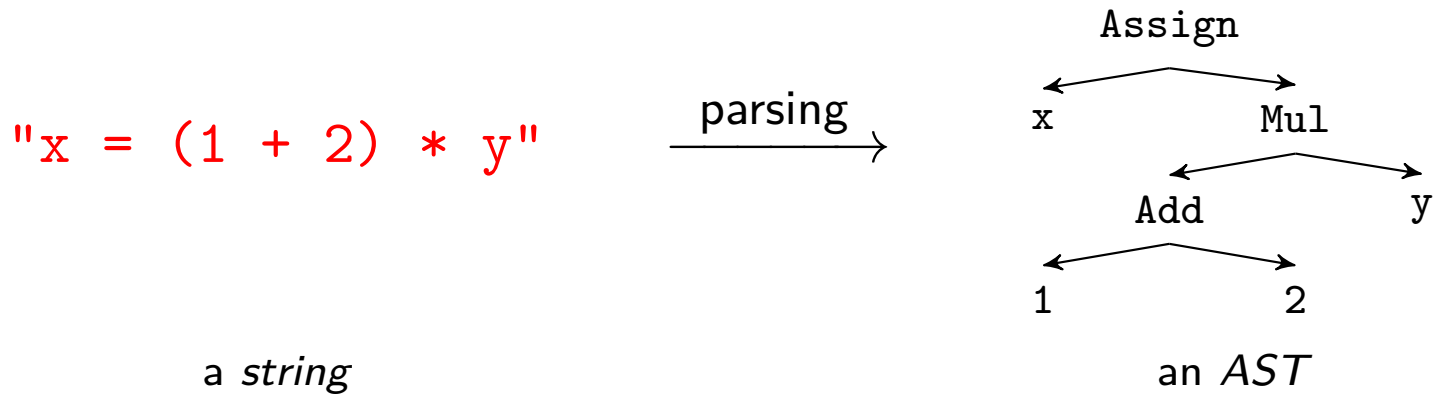

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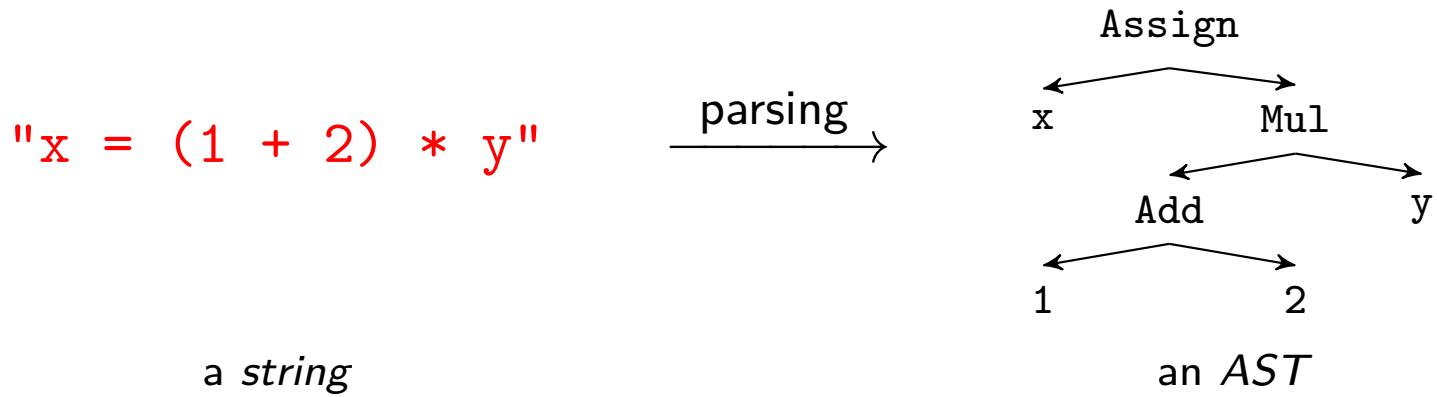

- Every analysis in this course works on the AST.

The Core of MiniPy

Let us define the **concrete syntax** of the **core** of MiniPy in BNF:

```
<expr>  ::= <num> | <id>
          | <expr> "+" <expr>
          | <expr> "*" <expr>
          | <expr> "<" <expr>
          | "(" <expr> ")"

<stmt>  ::= "pass"
          | <id> "=" <expr>
          | "if" <expr> ":" <block> "else" ":" <block>
          | "while" <expr> ":" <block>

<block> ::= <stmt>+
```

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<block> ::= <stmt>+
```

- **Nonterminals**: `<expr>`, `<stmt>`, `<block>`, `<num>`, `<id>`
- **Terminals**: `"+"`, `"*"`, `"<"`, `"("`, `"if"`, `"while"`, `"pass"`, `":"`, `"="`
- **Ambiguous** as written (`1 + 2 * 3` has two parse trees), so we fix **precedence** ($* > + > <$) and **associativity** (all left).

Abstract Syntax

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And its **abstract syntax**:

$$\begin{array}{ll} \text{Expressions} & e ::= n \mid x \mid e \texttt{ + } e \mid e \texttt{ * } e \mid e \texttt{ < } e \\ \text{Statements} & s ::= \texttt{pass} \\ & \quad \mid x \texttt{ := } e \\ & \quad \mid \texttt{if } e \texttt{ then } s^+ \texttt{ else } s^+ \\ & \quad \mid \texttt{while } e \texttt{ do } s^+ \end{array}$$

where $n \in \mathbb{Z}$ and $x \in \mathbb{X}$.

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where $n \in \mathbb{Z}$ and $x \in \mathbb{X}$.

- No parentheses, no precedence, no ambiguity: the **tree** already says how the program is grouped.
- We write `:=` for assignment, to keep it apart from mathematical equality in the rules that follow.

The AST in Python – Expressions

```
@dataclass(frozen=True)
class Expr: pass

@dataclass(frozen=True)
class Num(Expr):
    n: int

@dataclass(frozen=True)
class Var(Expr):
    x: str

@dataclass(frozen=True)
class BinOp(Expr):
    op: str
    left: Expr
    right: Expr
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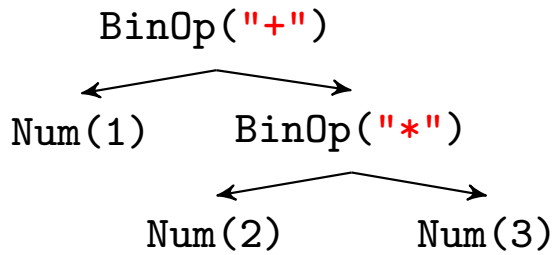
```

So `1 + 2 * 3` is built as:

```
BinOp("+",
      Num(1),
      BinOp("*",
            Num(2),
            Num(3)))
```



Precedence is gone — the shape carries it.

The AST in Python – Statements

```
@dataclass(frozen=True)
class Stmt: pass

@dataclass(frozen=True)
class Pass(Stmt): pass

@dataclass(frozen=True)
class Assign(Stmt):
    x: str
    e: Expr

@dataclass(frozen=True)
class If(Stmt):
    cond: Expr
    then: Block
    els: Block

@dataclass(frozen=True)
class While(Stmt):
    cond: Expr
    body: Block
```

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class While(Stmt):
    cond: Expr
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```

```
Block = tuple["Stmt", ...]
```

So `while i < n: i = i + 1` is built as:

```
While(
  BinOp("<", Var("i"), Var("n")),
  (Assign("i",
      BinOp("+", Var("i"), Num(1))),),
)
```

Indentation is gone — the tuple carries it.

Contents

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- Syntax says what programs **look like**. Semantics says what they **do**.
- The tool is **operational semantics**: rules that say how a program steps from one **state** to the next.
- A state $\sigma \in \mathbb{S} = \mathbb{X} \to \mathbb{V}$ maps variables to values.

Big-Step Semantics: Expressions

$\boxed{\sigma \vdash e \Rightarrow v}$ where $v ::= n \mid \texttt{true} \mid \texttt{false}$

"in state σ, expression e evaluates to value v."

$$\frac{}{\sigma \vdash n \Rightarrow n} \qquad \frac{}{\sigma \vdash x \Rightarrow \sigma(x)}$$

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With $\sigma = [x \mapsto 2]$:

$$\frac{\dfrac{\dfrac{}{\sigma \vdash x \Rightarrow 2} \qquad \dfrac{}{\sigma \vdash 3 \Rightarrow 3}}{\sigma \vdash x \texttt{ * } 3 \Rightarrow 6} \qquad \dfrac{}{\sigma \vdash 10 \Rightarrow 10}}{\sigma \vdash x \texttt{ * } 3 \texttt{ < } 10 \Rightarrow \texttt{true}}$$

Big-Step Semantics: Statements

$\boxed{\sigma \vdash s \Rightarrow \sigma'}$ *"running s in σ ends in σ'."*

$$\frac{\sigma \vdash e \Rightarrow v}{\sigma \vdash x := e \Rightarrow \sigma[x \mapsto v]} \qquad \frac{}{\sigma \vdash \texttt{pass} \Rightarrow \sigma}$$

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Small-Step Semantics

Big-step jumps from start to finish. Sometimes we want the **path**:

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- A non-terminating loop is now an **infinite sequence** of steps, not a missing derivation.
- We will use big-step for the interpreter, and small-step thinking when an analysis needs to reason about a single step.

The Interpreter

```
Value = int | bool                    #  v ::= n | true | false
State = dict[str, Value]              #  s in S = X -> V

def eval_expr(e: Expr, s: State) -> Value:
    match e:
        case Num(n):              return n
        case Var(x):              return s[x]
        case BinOp("+", l, r):    return eval_expr(l, s) + eval_expr(r, s)
        case BinOp("*", l, r):    return eval_expr(l, s) * eval_expr(r, s)
        case BinOp("<", l, r):    return eval_expr(l, s) < eval_expr(r, s)
        case _:                   raise NotImplementedError(e)

def exec_stmt(st: Stmt, s: State) -> State:
    match st:
        case Assign(x, e):
            return {**s, x: eval_expr(e, s)}
        case If(c, then, els):
            return exec_block(then if eval_expr(c, s) else els, s)
        case While(c, body):
            while eval_expr(c, s):
                s = exec_block(body, s)
            return s
        case _:                   raise NotImplementedError(st)
```

Lists Need a Heap

The core has no lists. Add them, and something new happens:

```
xs = [1, 2]
ys = xs
ys[0] = 7
r = xs[0]      # 7, not 1
```

`xs` and `ys` are **aliases**: two names for one list.

A state $\sigma : \mathbb{X} \to \mathbb{V}$ cannot say that — it has no notion of "the same list."

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So a list is a **location** ℓ, and a **heap** says what is stored there:

$$v ::= n \mid \texttt{true} \mid \texttt{false} \mid \ell \qquad\qquad H \in \mathbb{H} = \mathbb{L} \xrightarrow{\text{fin}} \mathbb{V}^*$$

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Every judgment now takes a heap in and gives a heap out:

$$\boxed{\langle H, \sigma \rangle \vdash e \Rightarrow \langle v, H' \rangle} \qquad\qquad \boxed{\langle H, \sigma \rangle \vdash s \Rightarrow \langle H', \sigma' \rangle}$$

The old rules only **thread** H through, unchanged.

Three Rules Touch the Heap

$$\frac{\langle H_{i-1}, \sigma\rangle \vdash e_i \Rightarrow \langle v_i, H_i\rangle \quad (1 \le i \le k) \qquad \ell \notin \mathsf{dom}(H_k)}{\langle H_0, \sigma\rangle \vdash [e_1, \ldots, e_k] \Rightarrow \langle \ell, H_k[\ell \mapsto (v_1, \ldots, v_k)]\rangle}$$

"*a list literal* **allocates** *a fresh location.*"

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"a list literal **allocates** *a fresh location."*

$$\frac{\begin{array}{c}\langle H, \sigma\rangle \vdash e_1 \Rightarrow \langle \ell, H_1\rangle \\ \langle H_1, \sigma\rangle \vdash e_2 \Rightarrow \langle n, H_2\rangle \qquad H_2(\ell) = (v_0, \ldots, v_{k-1}) \qquad 0 \le n < k\end{array}}{\langle H, \sigma\rangle \vdash e_1\,[e_2] \Rightarrow \langle v_n, H_2\rangle}$$

"indexing **loads** *from the heap."*

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PLRG

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"index assignment **stores** *into the heap — σ does not change."*

Three Rules Touch the Heap

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Nothing is shared behind the scenes: the interpreter threads H the same way.

The Interpreter, with a Heap

```
Value = int | bool | Loc                  #  v ::= n | true | false | l
Heap  = dict[Loc, tuple[Value, ...]]      #  H in L -> V*
def eval_expr(e: Expr, h: Heap, s: State) -> tuple[Value, Heap]:
    match e:
        case ListLit(items):
            vals = []
            for i in items:
                v, h = eval_expr(i, h, s)
                vals.append(v)
            loc = Loc(len(h))                          # l not in dom(h)
            return loc, {**h, loc: tuple(vals)}
        case Index(base, idx):
            loc, h = eval_expr(base, h, s)
            n, h = eval_expr(idx, h, s)
            return h[loc][n], h

def exec_stmt(st: Stmt, h: Heap, s: State) -> tuple[Heap, State]:
    match st:
        case IndexAssign(x, idx, e):
            loc = s[x]
            n, h = eval_expr(idx, h, s)
            v, h = eval_expr(e, h, s)
            return {**h, loc: h[loc][:n] + (v,) + h[loc][n + 1:]}, s
```

The Whole Language

A MiniPy program is **one function**, and `return` is its **last line**:

```
def main(n, uid):          # parameters: the input
    ...
    return r               # last line: the output
```

$$\langle \emptyset, [x_i \mapsto v_i] \rangle \vdash s \Rightarrow \langle H', \sigma' \rangle \qquad \langle H', \sigma' \rangle \vdash e \Rightarrow \langle v, H'' \rangle$$

"run the body from the arguments, then evaluate e."

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"run the body from the arguments, then evaluate e."

- No calls — not even `input()` or `print()`. Input comes in through the parameters and goes out through `return`.
- Also there: `str` with `+`, `<= == !=`, `and or not`, unary `-`, and `None`.
- Every rule is written out in the spec on the course page: **minipy-spec.pdf**

Contents

Python Already Has a Grammar

This course targets MiniPy, a small subset of Python. Python publishes both of the things we just wrote down:

Python Already Has a Grammar

PLRG

This course targets MiniPy, a small subset of Python. Python publishes both of the things we just wrote down:

- concrete syntax, as a grammar

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And the `ast` module **parses for us**. We never write a parser.

Parsing with the ast Module

```
>>> import ast
>>> print(ast.dump(ast.parse("x = 1 + 2"), indent=2))
Module(
  body=[
    Assign(
      targets=[Name(id='x', ctx=Store())],
      value=BinOp(
        left=Constant(value=1),
        op=Add(),
        right=Constant(value=2)))])
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- Same shape as our AST, with more detail than we need (`ctx`, positions, and a hundred node types we do not support).

Normalization

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So we **normalize** Python's AST into ours, and **reject** everything else.

```
def expr(node: ast.expr) -> Expr:
    match node:
        case ast.Constant(value=int(n)):
            return Num(n)
        case ast.Name(id=x):
            return Var(x)
        case ast.BinOp(left=l, op=op, right=r) if type(op) in BINOPS:
            return BinOp(BINOPS[type(op)], expr(l), expr(r))
        case ast.Compare(left=l, ops=[op], comparators=[r]):
            return BinOp(CMPOPS[type(op)], expr(l), expr(r))
        case _:
            raise Unsupported(node)
```

Using It

Download `syntax.py` and `interp.py` from the course page:

plrg.korea.ac.kr/courses/sws128

```
>>> from syntax import parse
>>> from interp import run
>>> src = """
... def sum(n):
...     i = 0
...     s = 0
...     while i <= n:
...         s = s + i
...         i = i + 1
...     return s
... """
>>> parse(src)
Prog(name='sum', params=('n',), body=(Assign(x='i', e=Num(n=0)),
Assign(x='s', e=Num(n=0)), While(...)), ret=Var(x='s'))
>>> run(parse(src), [5])
15
```

A Caution

We borrow Python's **syntax**, not its **semantics**. They mostly agree — but not always.

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- Python **chains**: $1 < 2$ and $2 < 3$, so `x` is `True`.
- MiniPy has one binary `<`: $(1 < 2) < 3$, that is `true` < 3.

Summary

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1. Syntax
    - Concrete Syntax
    - Abstract Syntax
2. Semantics
    - Big-Step Semantics
    - Small-Step Semantics
    - The Interpreter
    - Adding a Heap
3. Riding on Python
    - Grammar and Parsing
    - Normalization
    - Running It
    - A Caution

Next Lecture

- Control Flow Graphs

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