This Lecture

• Parser generators ("compiler compilers")
• The parser generator Happy
• A TXL parser written using Happy
• A TXL interpreter written using Happy
Parser Generators (1)

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E.g., this simple grammar (from the prev. lect.)

\[
\begin{align*}
S & \rightarrow aABe \\
A & \rightarrow bcA \mid c \\
B & \rightarrow d
\end{align*}
\]

gives rise to a 10 state LR(0) DFA!
Parser Generators (2)

An LR(0) DFA recognizing viable prefixes for

\[ S \rightarrow aABe \quad A \rightarrow bcA \mid c \quad B \rightarrow d \]
Parser Generators (3)

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Parser Generators (4)

Consider an LR shift-reduce parser:
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- Some of the actions when parsing $abccde$:

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- A **reduction** corresponds to a derivation step in the grammar (an LR parser performs a rightmost derivation in reverse).
Parser Generators (5)

- At a reduction, the terminals and non-terminals of the RHS of the production (the **handle**) are on the parse stack, associated with **semantic information** or **semantic value**; e.g., the corresponding AST fragments, expression values.
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Construction of AST, evaluation of expressions, etc. proceeds in *bottom-up* order.
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- **Cup**: LALR parser generator for Java.
Parser Generators (7)


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We are going to develop a TXL parser using Happy. The TXL CFG:

\[
\begin{align*}
    TXLProgram & \rightarrow \ Exp \\
    Exp & \rightarrow \ AddExp \\
    AddExp & \rightarrow \ MulExp \\
    & \quad | \ AddExp + MulExp \\
    & \quad | \ AddExp - MulExp
\end{align*}
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Happy Parser for TXL (1)

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Note: \textit{Left-recursive!} (To impart associativity.) LR parsers have no problems with left- or right-recursion (except right recursion uses more stack).
The TXL CFG continued:

\[
\begin{align*}
    \text{MulExp} & \rightarrow \text{PrimExp} \\
    & \quad | \text{MulExp} \ast \text{PrimExp} \\
    & \quad | \text{MulExp} / \text{PrimExp} \\
    \text{PrimExp} & \rightarrow \text{IntegerLiteral} \\
    & \quad | \text{Identifier} \\
    & \quad | ( \text{Exp} ) \\
    & \quad | \text{let Identifier} = \text{Exp} \text{ in } \text{Exp}
\end{align*}
\]
Haskell datatype for tokens:

```haskell
data Token = T_Int Int
            | T_Id Id
            | T_plus
            | T_Minus
            | T_Times
            | T_Divide
            | T_LeftPar
            | T_RightPar
            | T_Equal
            | T_Let
            | T_In
```
Haskell datatypes for AST:

```haskell
data BinOp = Plus | Minus | Times | Divide

data Exp = LitInt Int
         | Var Id
         | BinOpApp BinOp Exp Exp
         | Let Id Exp Exp
```
A simple Happy parser specification:

```haskell
{ Module Header }
%name ParserFunctionName
%tokentype { TokenTypeName }

%token

Specification of Terminal Symbols
%%
Grammar productions with semantic actions

{ Further Haskell Code }
```
The terminal symbol specification specifies terminals to be used in productions and relates them to Haskell constructors for the tokens:

```
%token
  int         { T_Int $$ }
  ident      { T_Id $$ }
  '+'        { T_Plus }
  '-'        { T_Minus }
  '='        { T_Equal }
  let        { T_Let }
  in         { T_In }
```

...
• The code fragment between curly braces is a Haskell pattern that is matched against the actual tokens returned by the parsing function.
Happy Parser for TXL (7)

- The code fragment between curly braces is a Haskell `pattern` that is matched against the actual tokens returned by the parsing function.
- If this pattern contains the special variable $$, then the corresponding part of the matched token becomes the semantic value. Examples: `T_Int $$, T_Id $$`
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- Otherwise the entire token becomes the semantic value. Examples: `T_Plus`, `T_In`

- The semantic values of different terminal symbols may thus have different types.
The grammar productions are written in BNF, with an additional semantic action defining the semantic value for each production:

add_exp
  : mul_exp {$1}
  | add_exp '+' mul_exp {BinOpApp Plus $1 $3}
  | add_exp '-' mul_exp {BinOpApp Minus $1 $3}

mul_exp
  : prim_exp {$1}
  | mul_exp '*' prim_exp {BinOpApp Times $1 $3}
  | mul_exp '/' prim_exp {BinOpApp Divide $1 $3}
It is also possible to add type annotations:

```
add_exp :: { Exp }
```

```
add_exp
  : mul_exp {1}
  | add_exp '+' mul_exp {BinOpApp Plus $1 $3}
  | add_exp '-' mul_exp {BinOpApp Minus $1 $3}
```

Most useful when semantic values are of different types.

See `HappyTXL.y` for the complete example.
Context-free grammars are often initially ambiguous. Consider the grammar fragment:

\[
\text{Cmd} \quad \rightarrow \quad \ldots \\
\quad \mid \quad \text{if } \text{Exp} \text{ then } \text{Cmd} \\
\quad \mid \quad \text{if } \text{Exp} \text{ then } \text{Cmd} \text{ else } \text{Cmd}
\]

According to this grammar, a program fragment

\[
\text{if } e_1 \text{ then if } e_2 \text{ then } c_1 \text{ else } c_2
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In LR-parsing, ambiguous grammars lead to *shift/reduce* and *reduce/reduce* conflicts:
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- **shift/reduce**: some states have mixed complete and incomplete items:
  \[
  A \rightarrow a \cdot A \\
  A \rightarrow a \cdot b
  \]

  Should parser shift or reduce?
Shift/Red. and Red./Red. Conflicts (3)

- reduce/reduce: some states have more than one complete item:

\[ A \rightarrow a \cdot \]
\[ B \rightarrow a \cdot \]

Reduce, but by which production?
Shift/Red. and Red./Red. Conflicts (4)

- Shift/reduce conflicts often resolved by opting for shifting:
  - Typically the default option (e.g. Yacc, Bison, Happy)
  - Usually gives the desired result; e.g., resolves the dangling else problem in a natural way.
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- Reduce/reduce conflicts are worse as no reason to pick one production over another: grammar has to be manually disambiguated.
Precedence and Associativity

Happy (like e.g. Yacc and Bison) allows operator precedence and associativity to be explicitly specified to disambiguate a grammar:

```plaintext
%left '+' '-'
%left '*' '/'

exp : exp '+' exp { BinOpApp Plus $1 $3 }
    | exp '-' exp { BinOpApp Minus $1 $3 }
    | exp '*' exp { BinOpApp Times $1 $3 }
    | exp '/' exp { BinOpApp Divide $1 $3 }
    ...
```

See HappyTXL2.y for further details.
A TXL Interpreter (1)

The semantic actions do not have to construct an AST. An alternative is to *interpret* the code being parsed.
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The semantic actions do not have to construct an AST. An alternative is to interpret the code being parsed. Basic idea:

```latex
exp :: { Int }
exp
  : exp ' +' exp { $1 + $3 }
  | exp ' - ' exp { $1 - $3 }
  ...
```
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The semantic actions do not have to construct an AST. An alternative is to interpret the code being parsed. Basic idea:

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\begin{align*}
\text{exp} & : : \{ \text{Int} \} \\
\text{exp} & : \text{exp} \ '+' \text{exp} \ \{ $1 + $3 \} \\
& | \text{exp} \ '-' \text{exp} \ \{ $1 - $3 \} \\
& \ldots
\end{align*}
\]

But TXL has a \texttt{let}-construct \ldots
A TXL Interpreter (1)

The semantic actions do not have to construct an AST. An alternative is to interpret the code being parsed. Basic idea:

```
exp ::= { Int }
exp
  : exp ' +' exp { \$1 + \$3}
  | exp ' -' exp { \$1 - \$3}
  ...
```

But TXL has a let-construct . . .

**What about TXL VARIABLES??** E.g.:

```
let x = 3 in x + x, semantic value of x?
```
A TXL Interpreter (2)

One way:
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- Each semantic action returns a function of type
  \[ \text{Env} \rightarrow \text{Int} \]
  where (for example)
  \[ \text{Type Env} = \text{Id} \rightarrow \text{Int} \]
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  where (for example)
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- The semantic action for evaluating a composite expression passes on the environment. E.g. semantic action for +:
  \[
  \begin{array}{l}
  \mid \text{exp} \ '++' \ \text{exp} \\
  \{
  \text{\( \text{\backslash env \rightarrow \$1 \ env + \$3 \ env \) \}}}
  \end{array}
  \]
A TXL Interpreter (3)

- The semantic action for a variable looks up the variable value in the environment:

```plaintext
| ident { \env \rightarrow \env \ $1 } 
```
The semantic action for a variable looks up the variable value in the environment:
\[ \text{ident} \{ \text{env} \rightarrow \text{env} \; \text{let} \; v \} \]

The semantic action for \text{let} extends the argument environment and evaluates the body in the extended environment:
\[ \text{let ident ‘=’ exp in exp} \]
\[ \{ \text{env} \rightarrow \text{let} \; v = \}$4 \; \text{env} \]
\[ \text{in} \; \}$6 \; (\{i \rightarrow \text{if} \; i == \}$2 \]
\[ \text{then} \; v \]
\[ \text{else} \; \text{env} \; i)\} \]
A TXL Interpreter (4)

- A program gets evaluated by applying the overall result function to the empty environment:

\[ \_ \rightarrow \text{error "undefined variable"} \]

See HappyTXLInterpreter.y for further details.