CSL302: Compiler Design

Syntax Analysis

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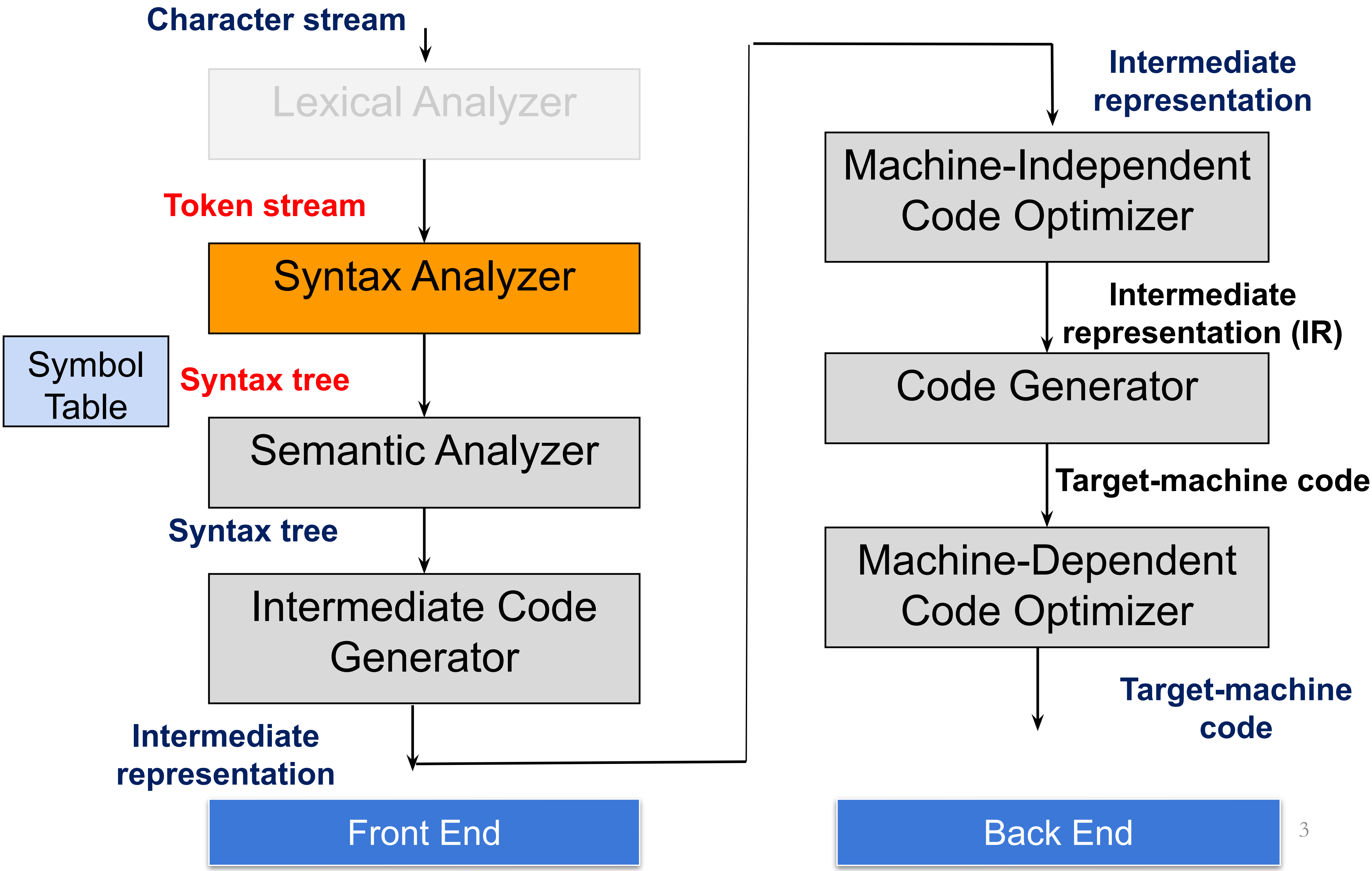
Acknowledgement

- Today’s slides are modified from that of
    - *Stanford University:*
        - *https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/*

Compiler Design



Character stream

Lexical Analyzer

Token stream

Syntax Analyzer

Symbol Table

Syntax tree

Semantic Analyzer

Syntax tree

Intermediate Code Generator

Intermediate representation

Front End

Intermediate representation

Machine-Independent Code Optimizer

Intermediate representation (IR)

Code Generator

Target-machine code

Machine-Dependent Code Optimizer

Target-machine code

Back End

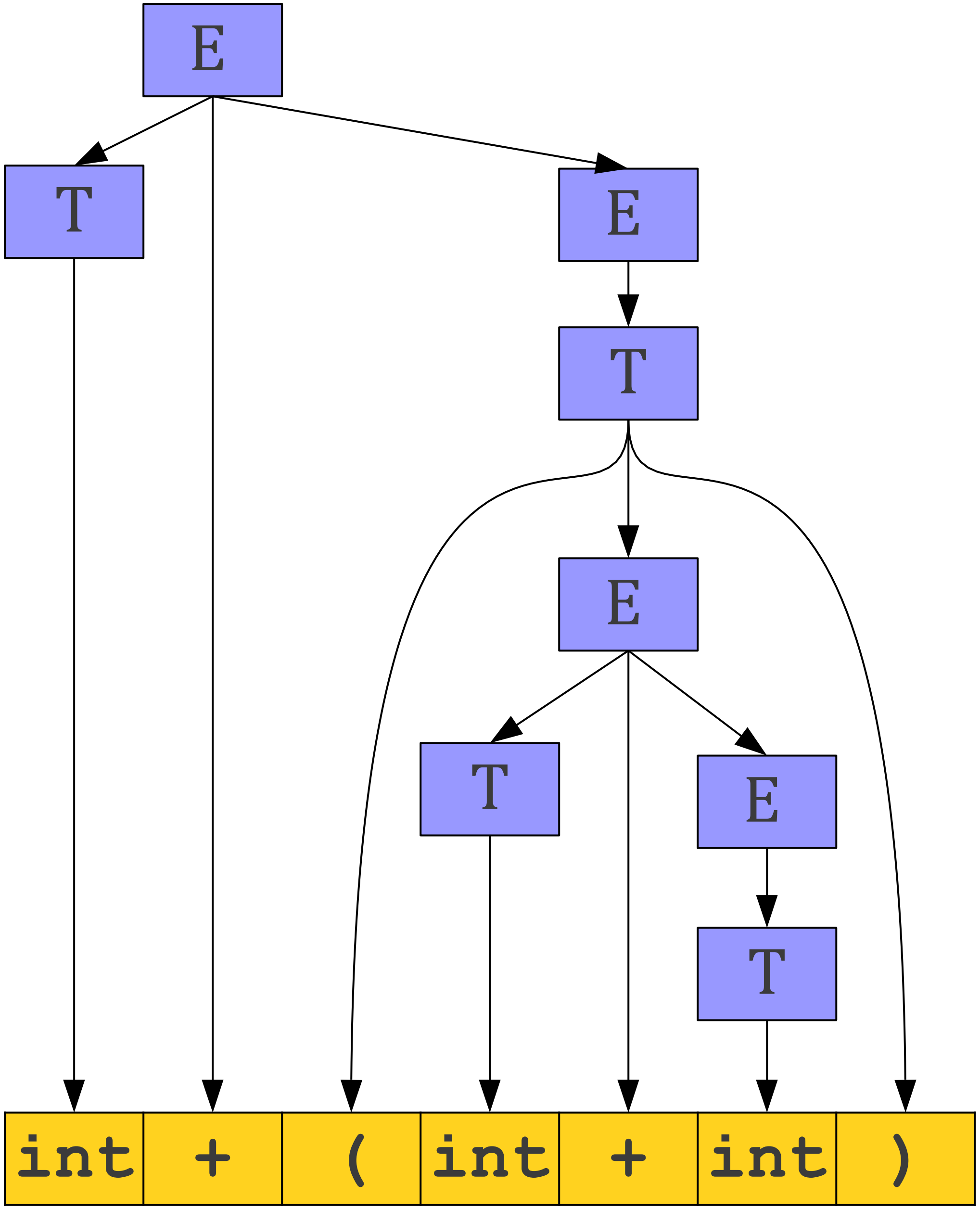
Recap: Parsing

E → T

E → T+ E

T → int

T → (E)



Different Types of Parsing

- **Top-Down Parsing**
  - Beginning with the start symbol, try to guess the productions to apply to end up at the user's program.

- **Bottom-Up Parsing**
  - Beginning with the user's program, try to apply productions in reverse to convert the program back into the start symbol.

Different Types of Parsing

- **Top-Down Parsing**
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Challenges in Top-Down Parsing

- Top-down parsing begins with virtually no information.
  - Begins with just the start symbol
- How can we know which productions to apply?
- In general, we can't.
  - There are some grammars for which the best we can do is guess and backtrack if we're wrong.

Parsing as a Search

- An idea: **treat parsing as a graph search**.
- Each node is a **sentential form** (a string of terminals and nonterminals derivable from the start symbol).
- There is an edge from node $\boldsymbol{\alpha}$ to node $\boldsymbol{\beta}$ iff $\boldsymbol{\alpha} \Rightarrow \boldsymbol{\beta}$.

Parsing as a Search

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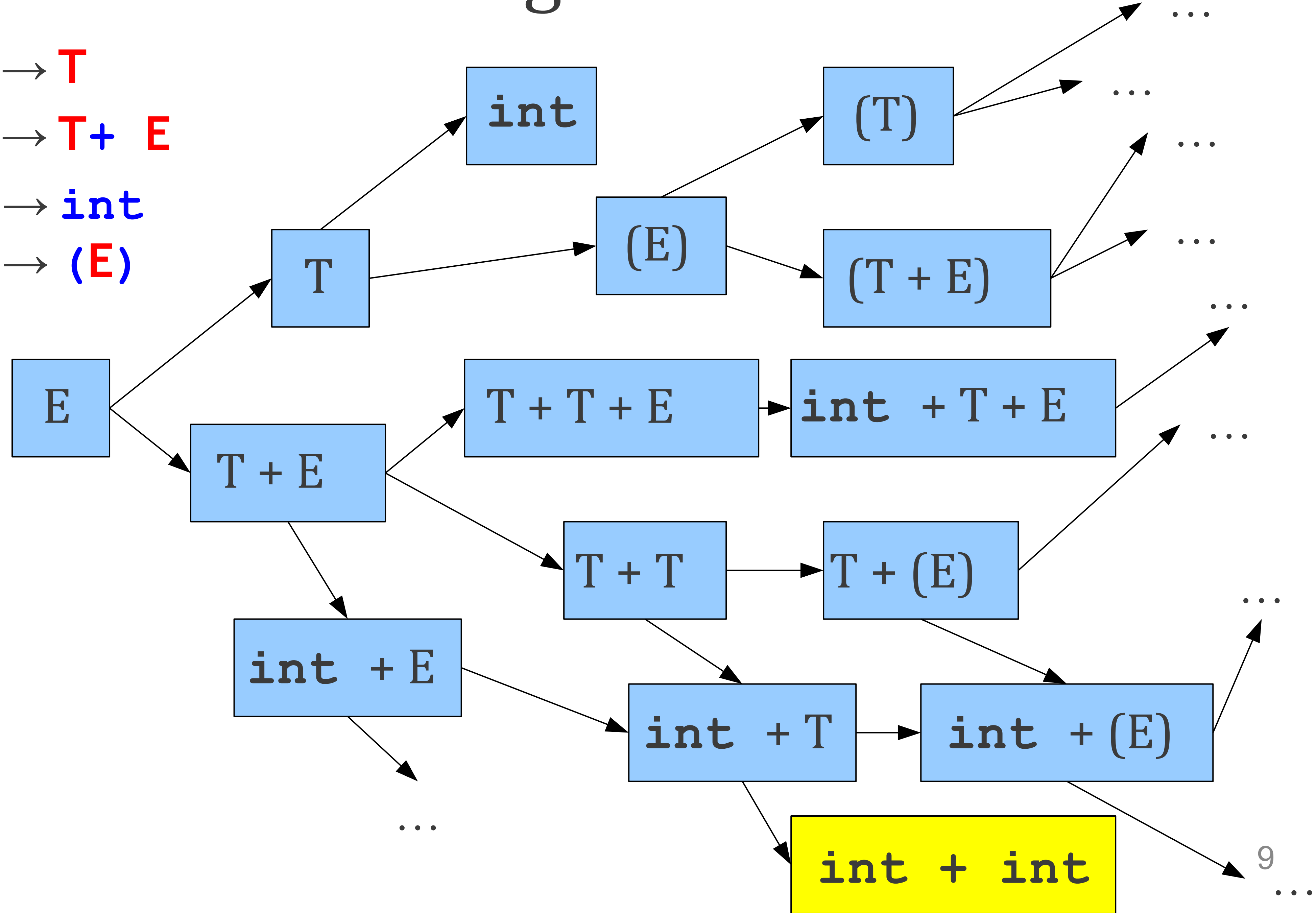

Parsing as a Search

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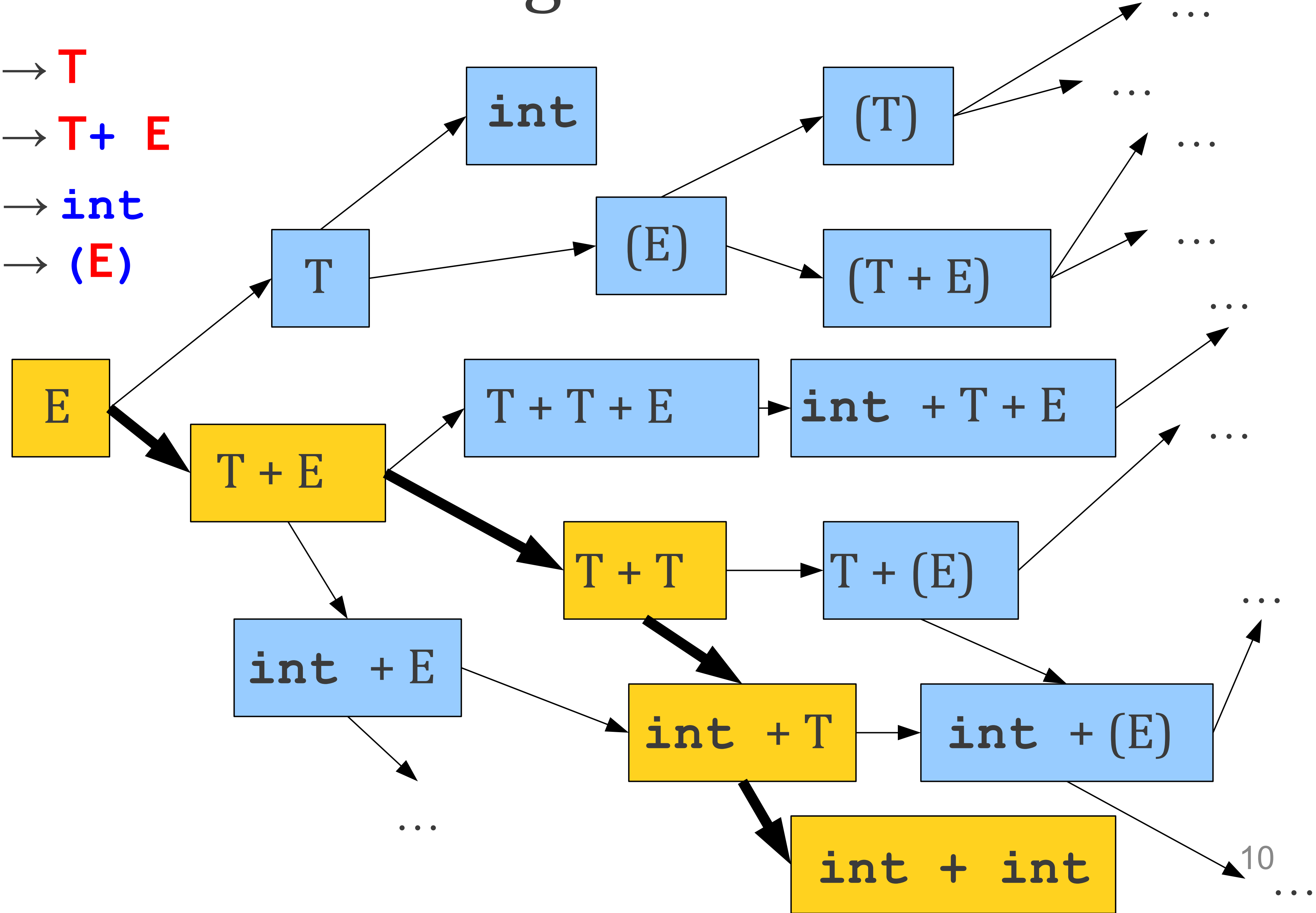


Our First Top-Down Algorithm

- **Breadth-First Search**
- Maintain a worklist of sentential forms, initially just the start symbol **S**.
- While the worklist isn't empty:
  - Remove an element from the worklist.
  - If it matches the target string, you're done.
  - Otherwise, for each possible string that can be derived in one step, add that string to the worklist.
- Can recover a parse tree by tracking what productions we applied at each step.

Breadth-First Search Parsing

Worklist

E → T

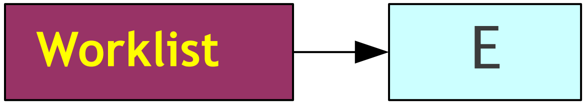
E → T + E

T → int

T → (E)

int + int

Breadth-First Search Parsing



E → T

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Breadth-First Search Parsing

Worklist

E

E → T

E → T + E

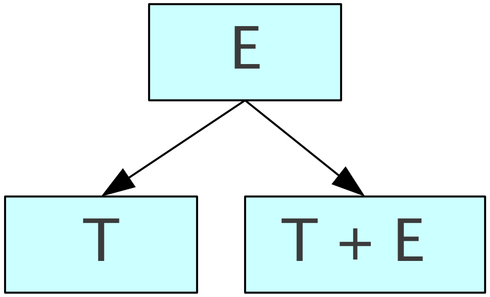
T → int

T → (E)

```
int + int
```

Breadth-First Search Parsing

Worklist



E → T

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T → int

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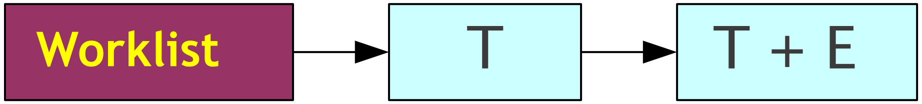
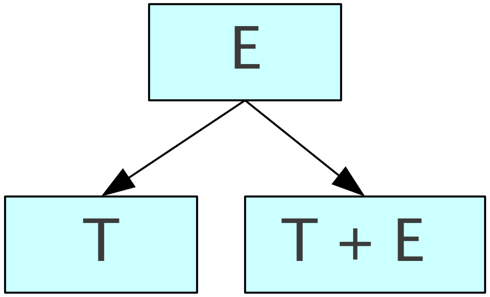
int + int

Breadth-First Search Parsing


Worklist
T
T + E


E
T
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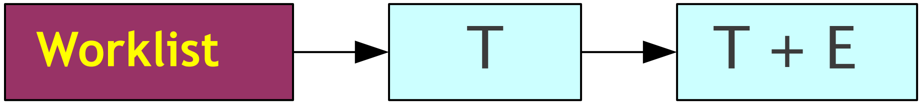

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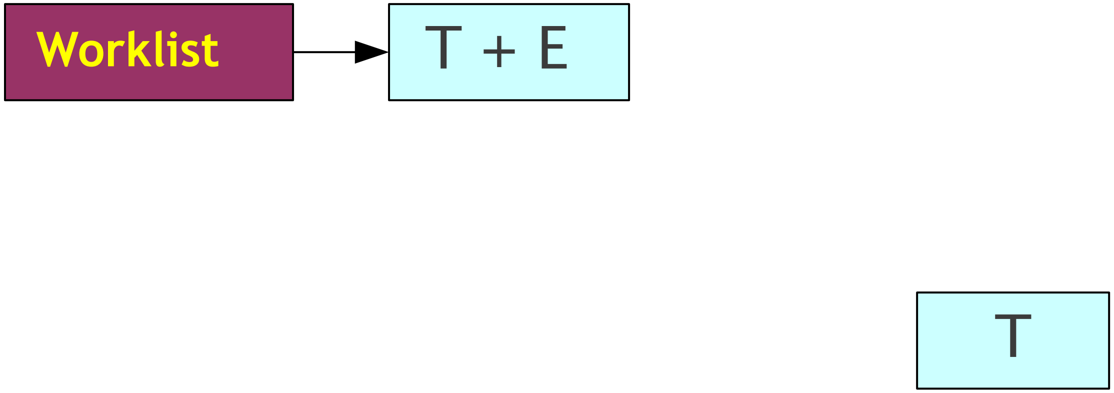

Worklist

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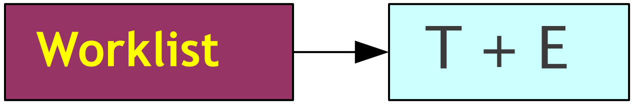

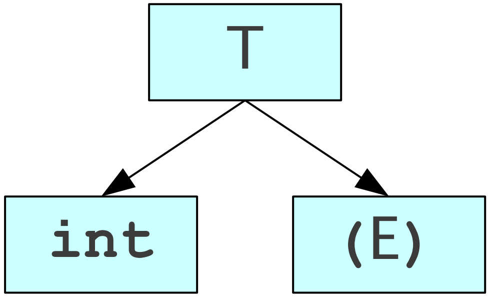

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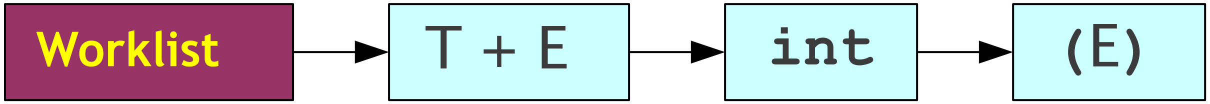

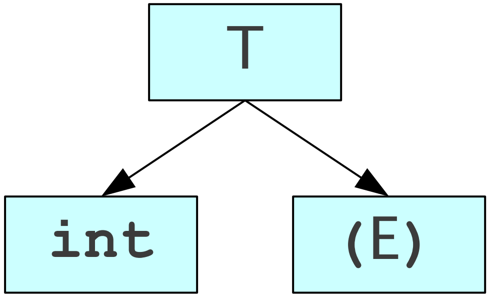

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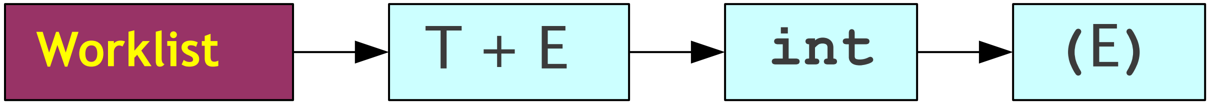

Worklist → T + E → int → (E)

E → T

E → T + E

T → int

T → (E)

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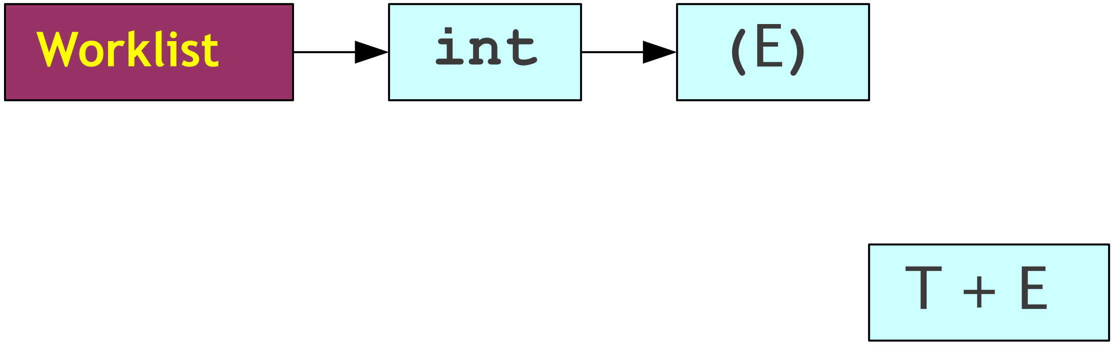
Breadth-First Search Parsing



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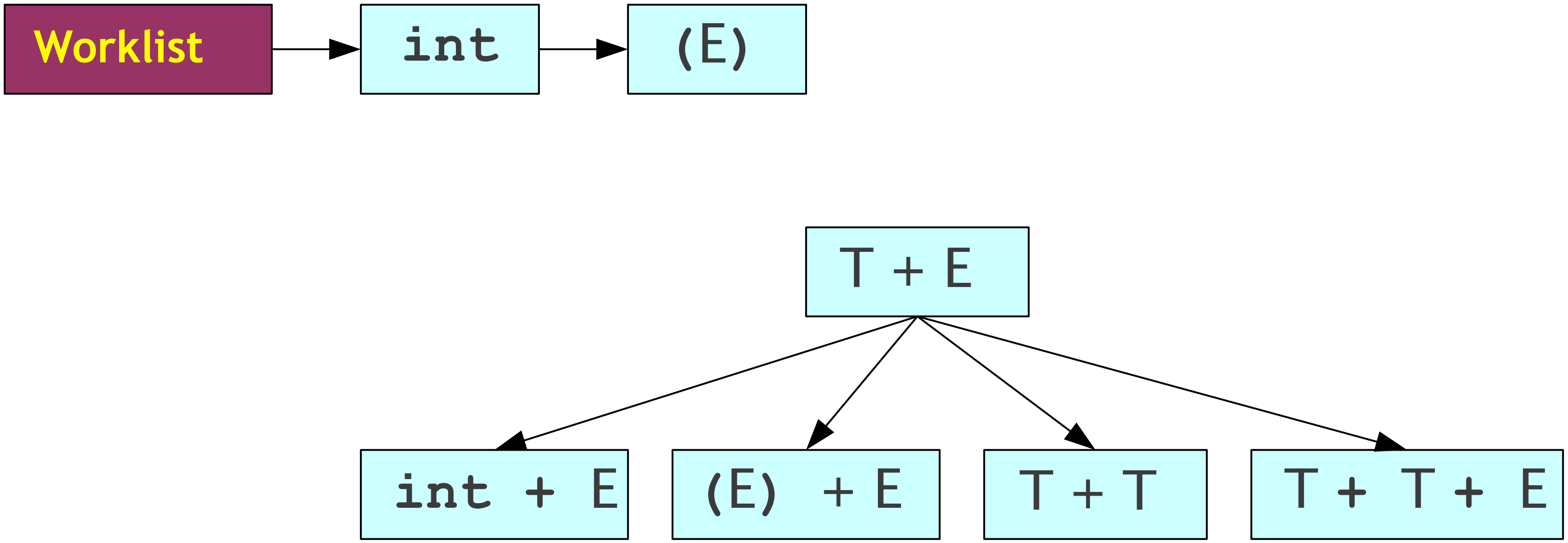


Worklist

int

(E)

T + E

int + E

(E) + E

T + T

T + T + E

E → T

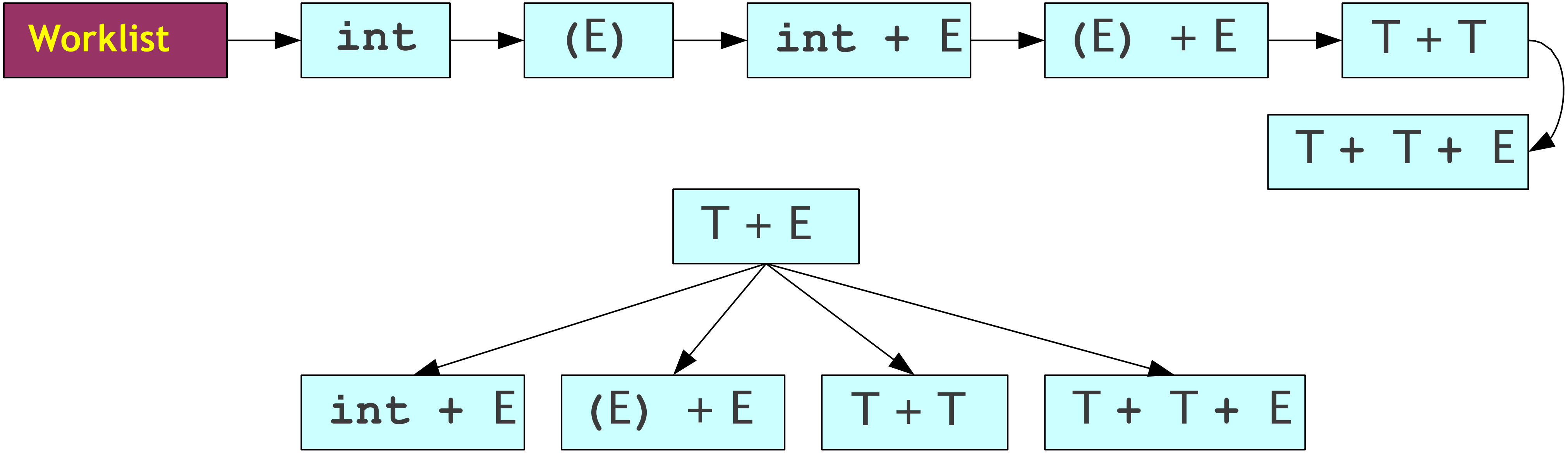
E → T + E

T → int

T → (E)

int + int

Breadth-First Search Parsing



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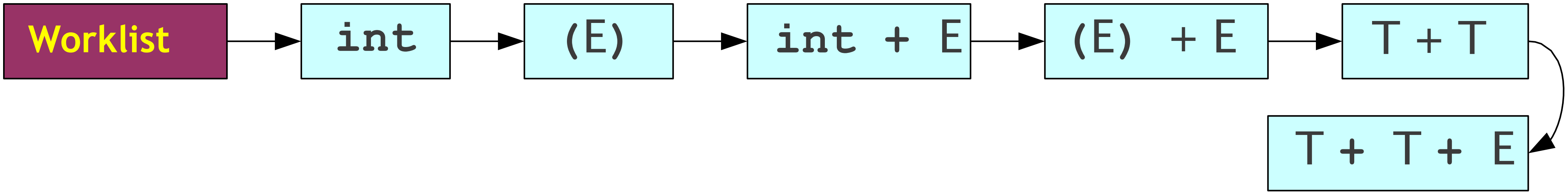

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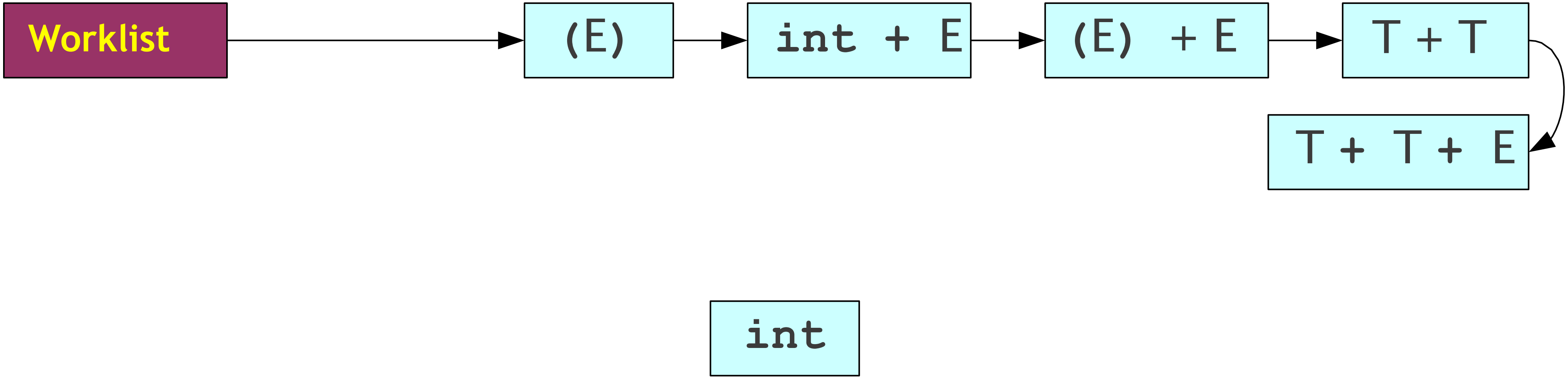

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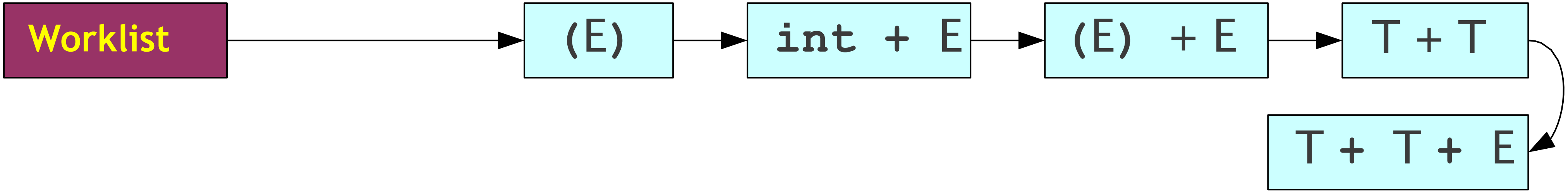

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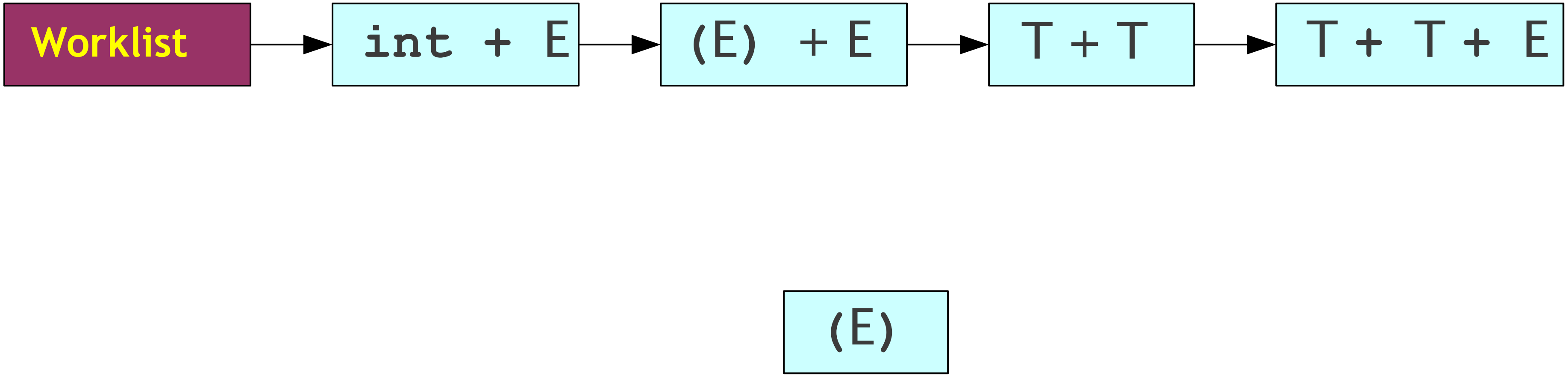

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T + T + E

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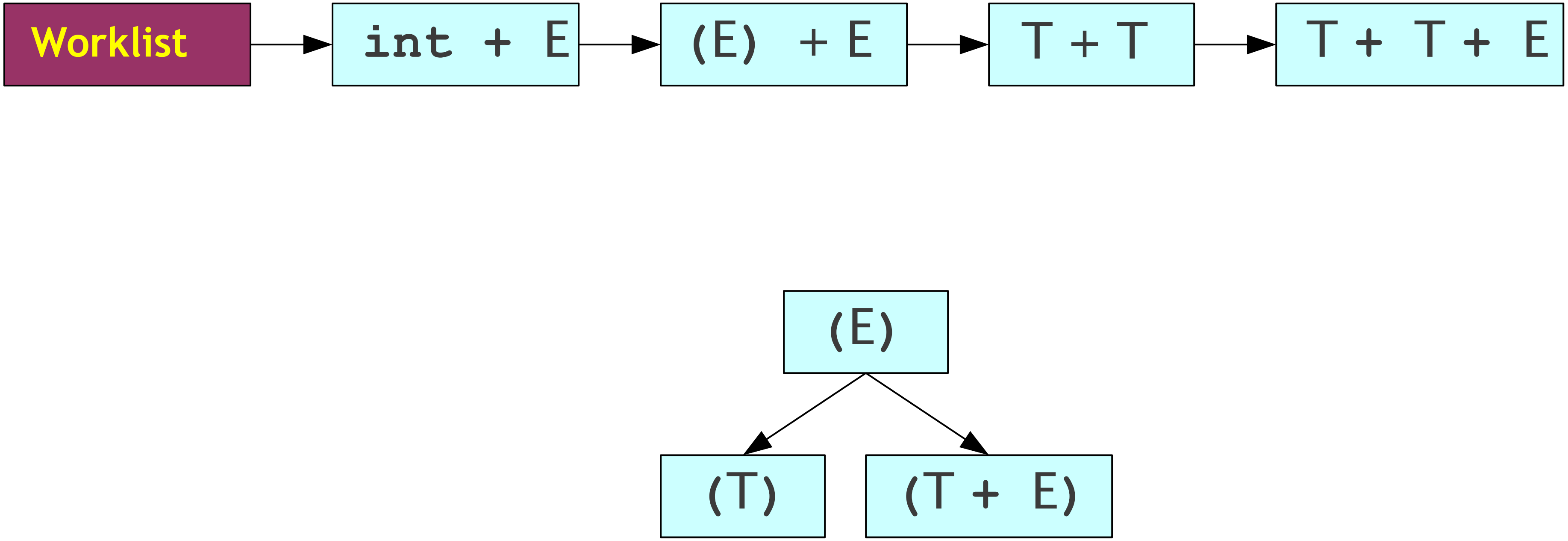

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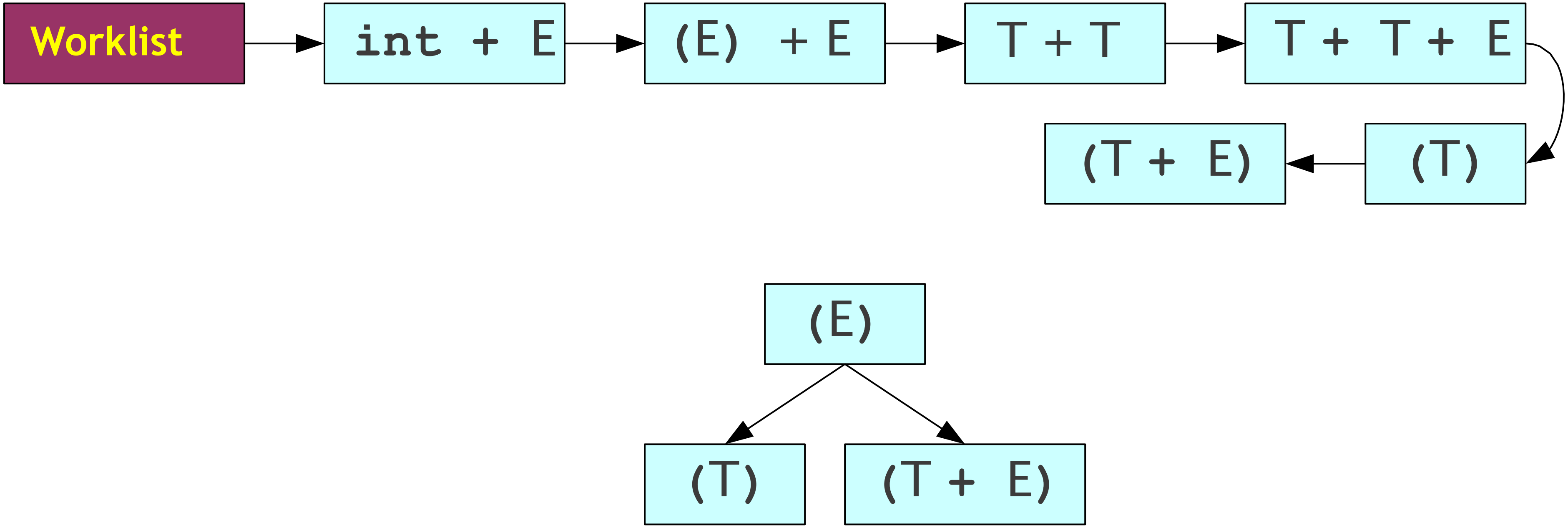

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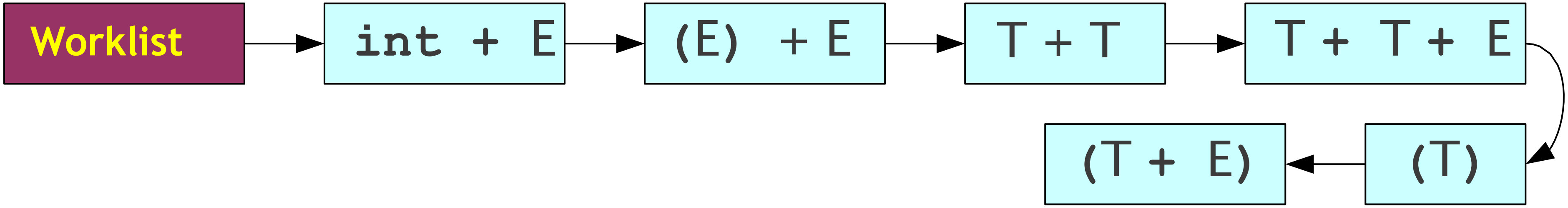

Worklist

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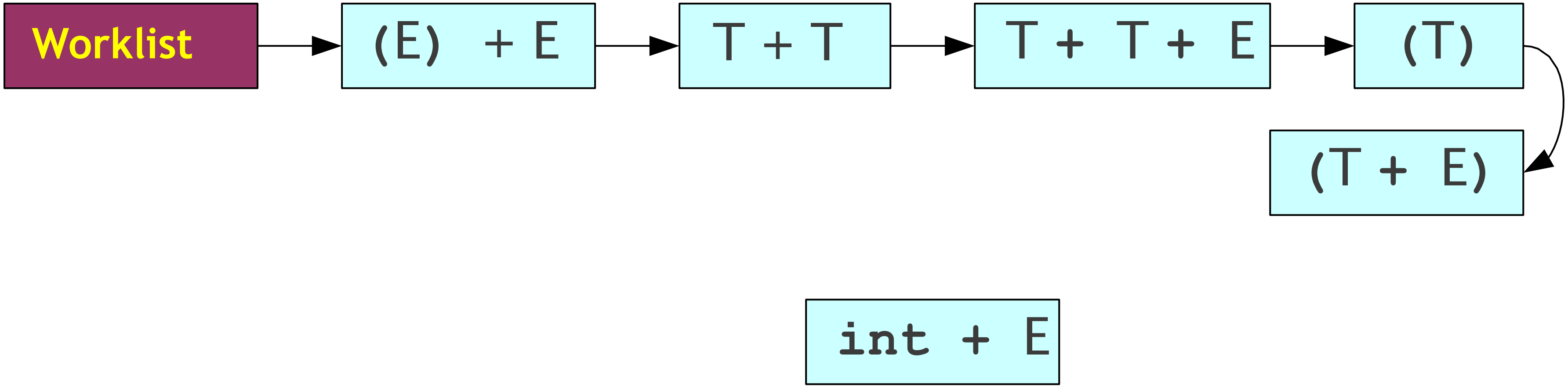

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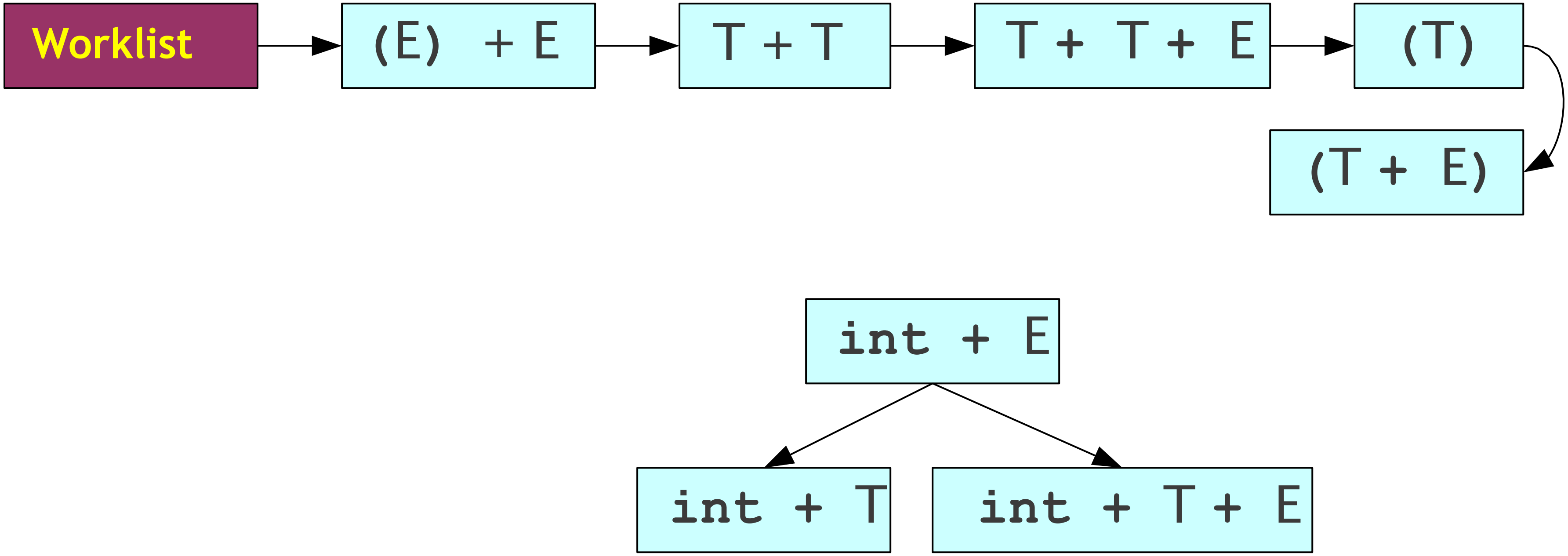

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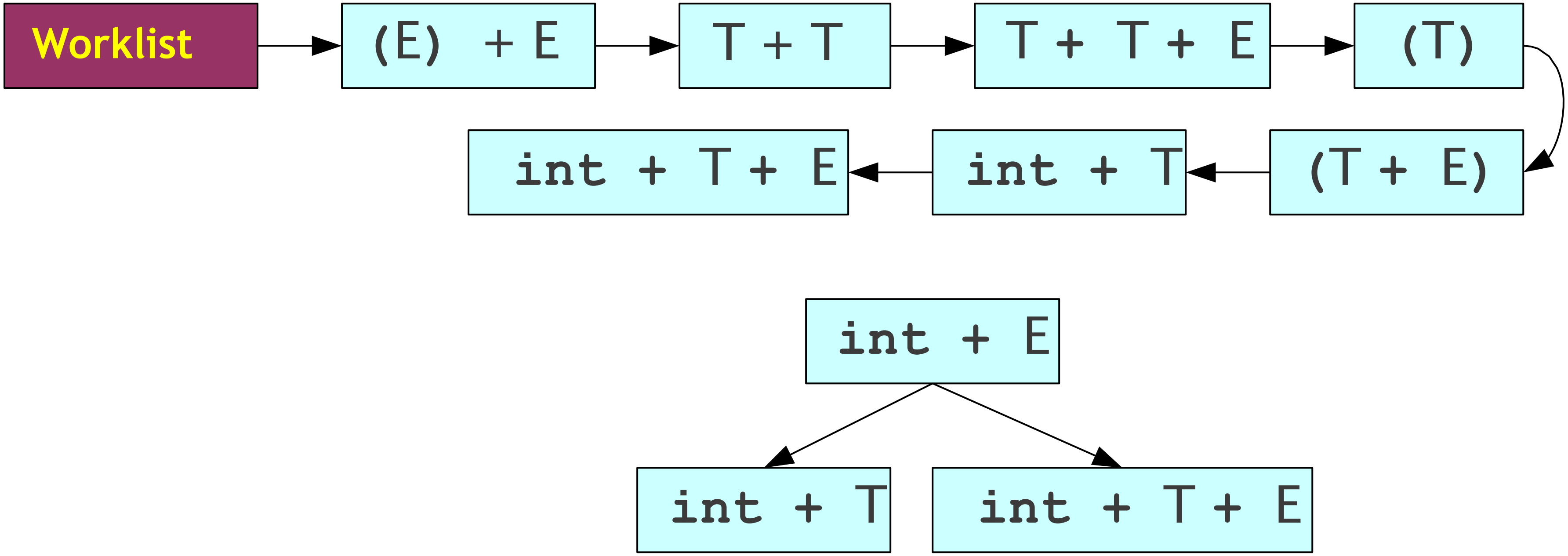

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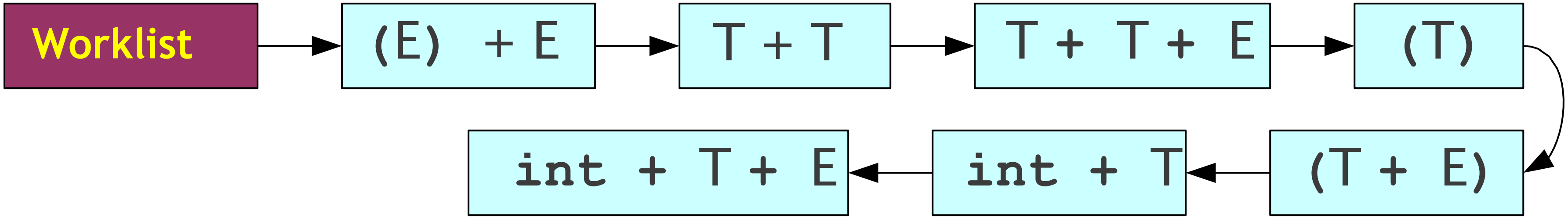

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T + T + E

(T)

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int + T

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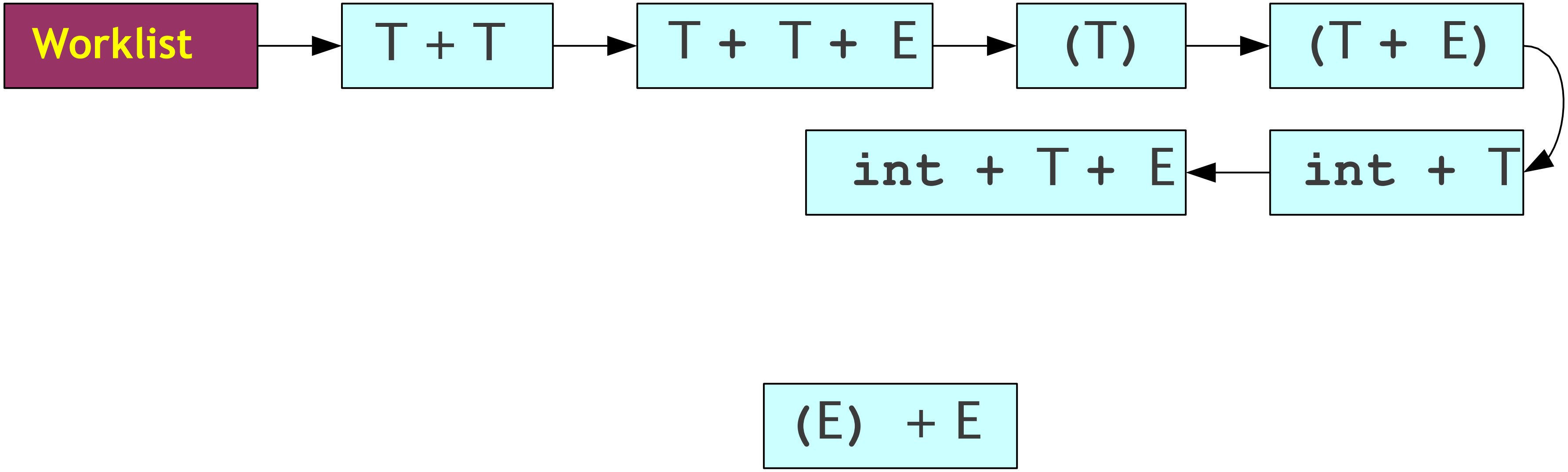

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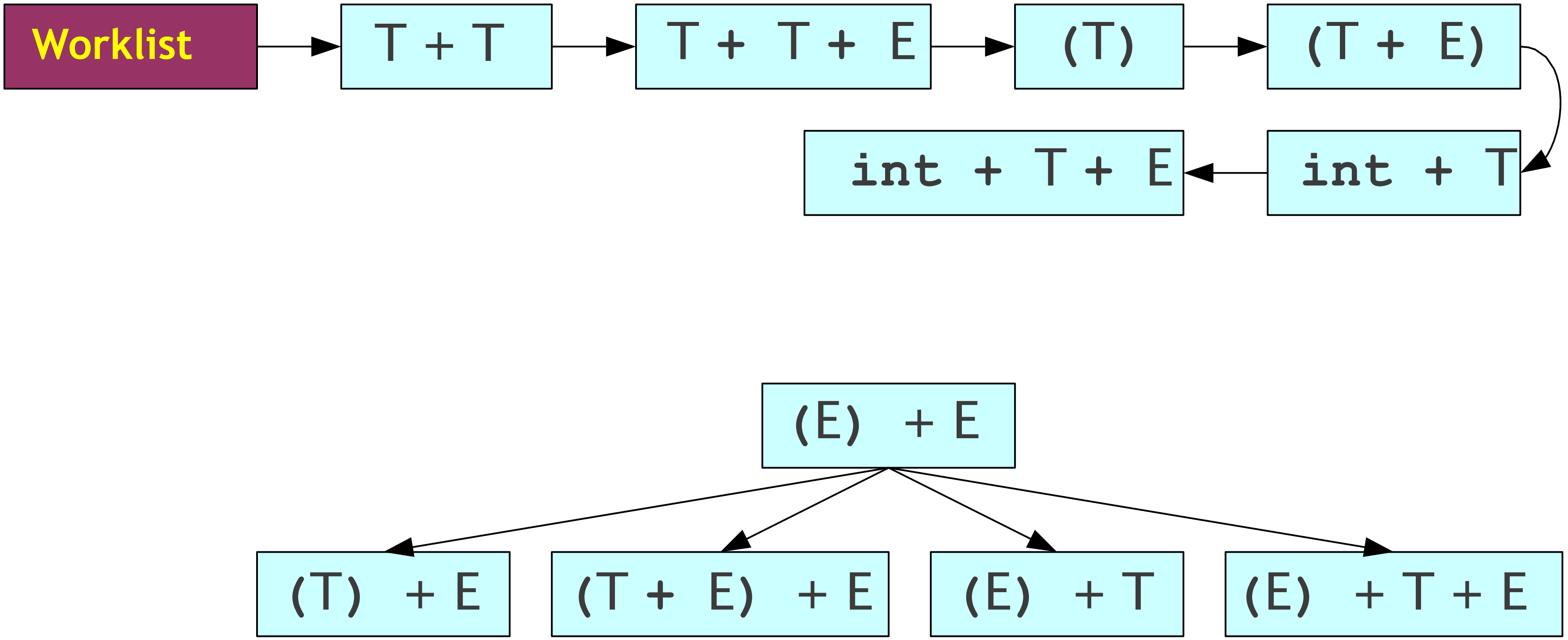

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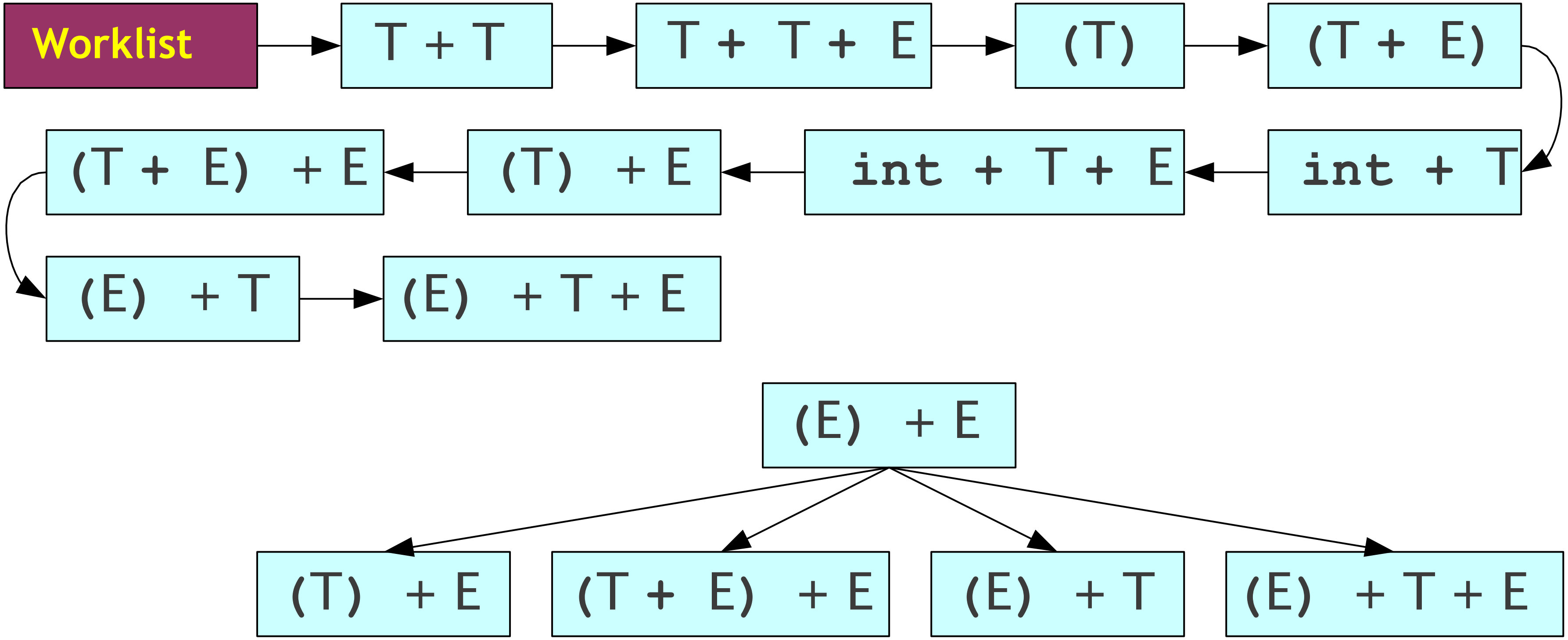

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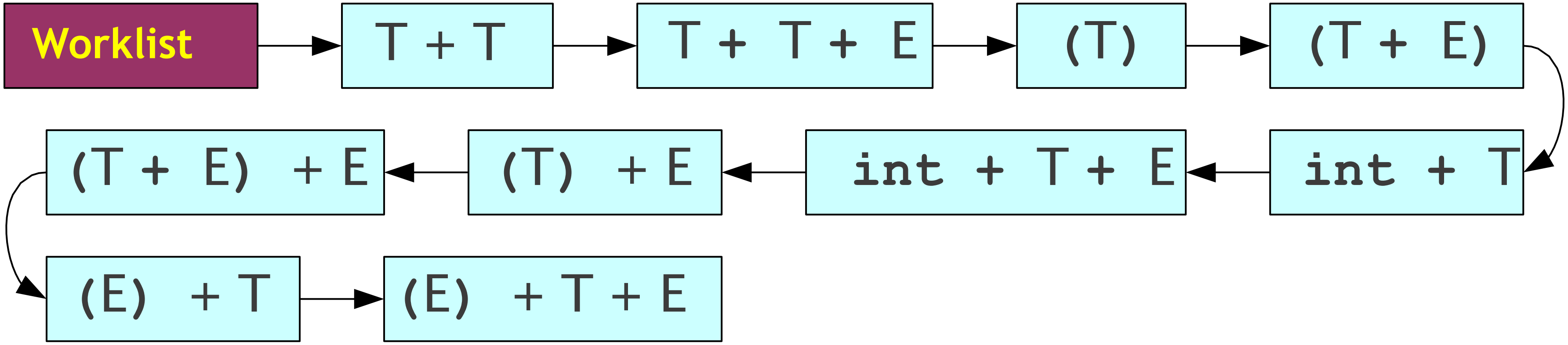

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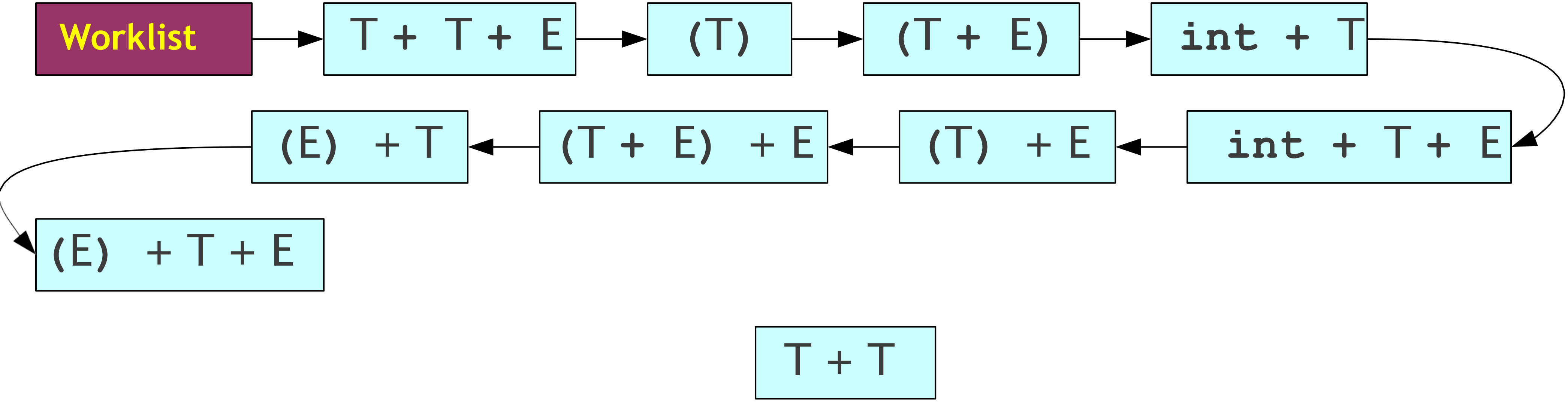

Worklist

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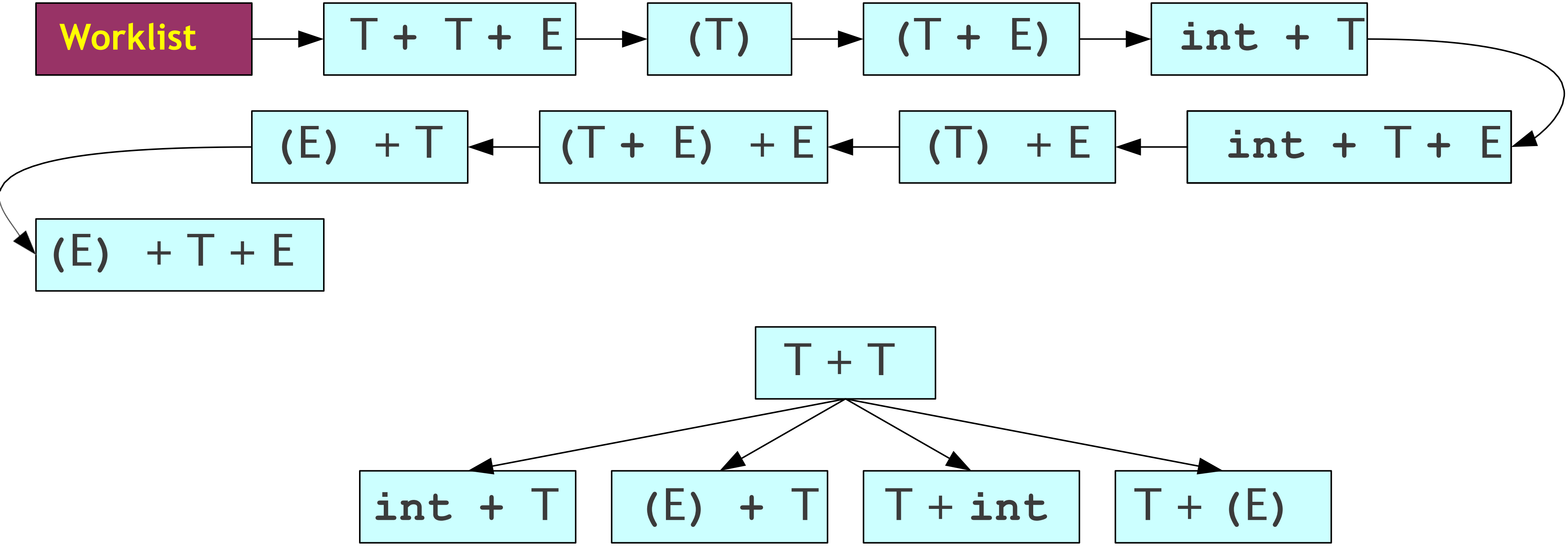

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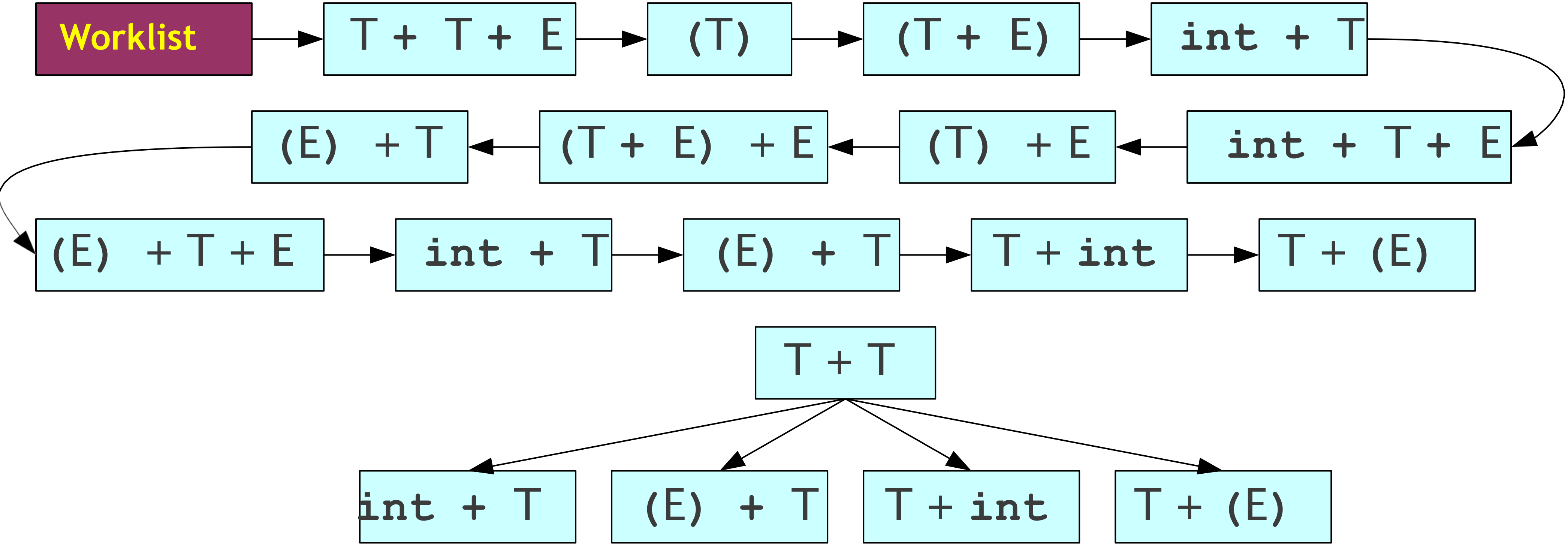

Worklist

T + T + E

(T)

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int + T + E

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(E) + T

T + int

T + (E)

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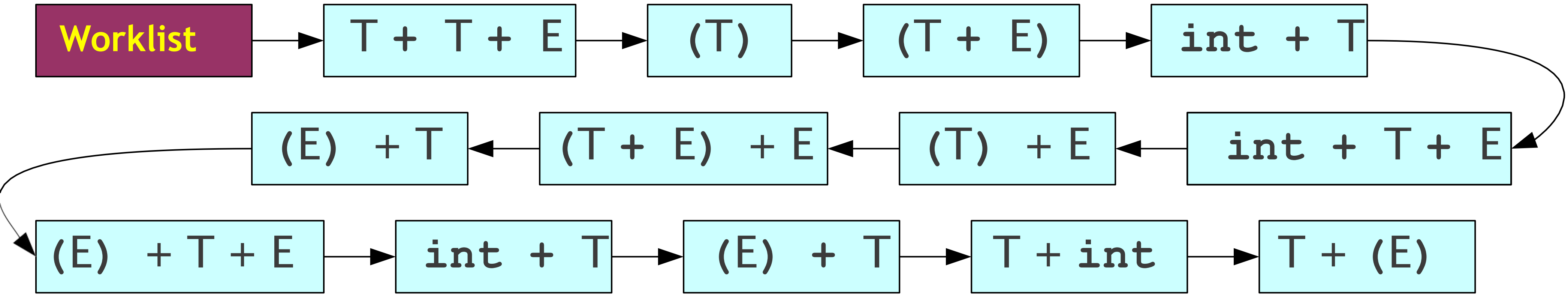

Worklist

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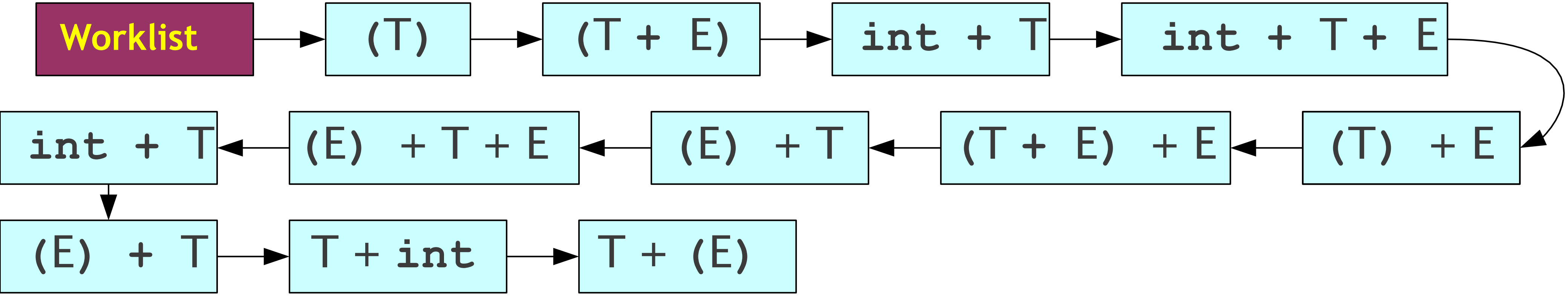

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(T) + E

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(E) + T + E

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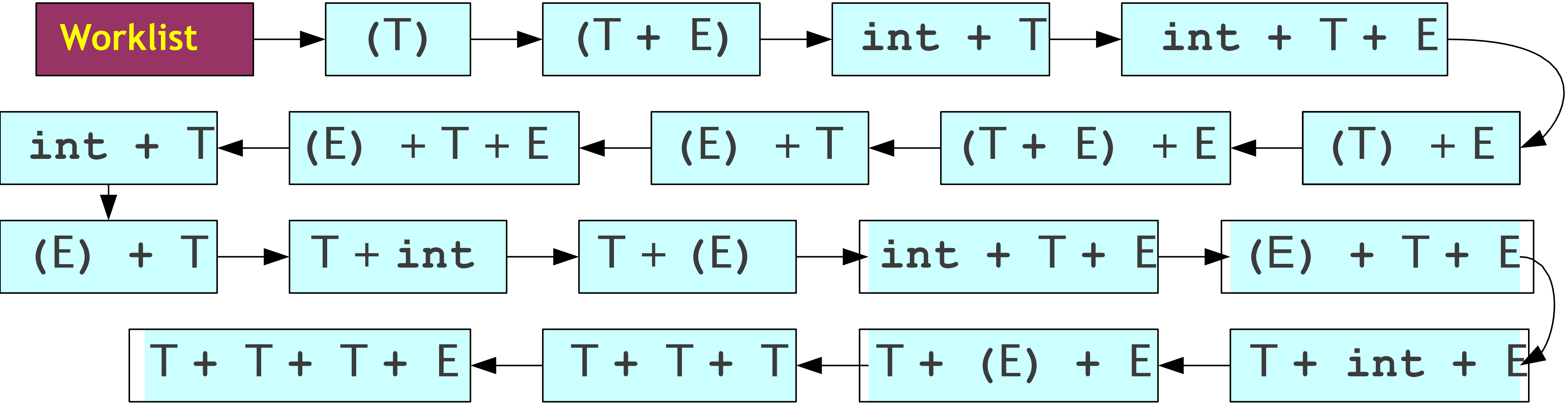

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(E) + T

(E) + T + E

int + T

(E) + T

T + int

T + (E)

int + T + E

(E) + T + E

T + int + E

T + (E) + E

T + T + T

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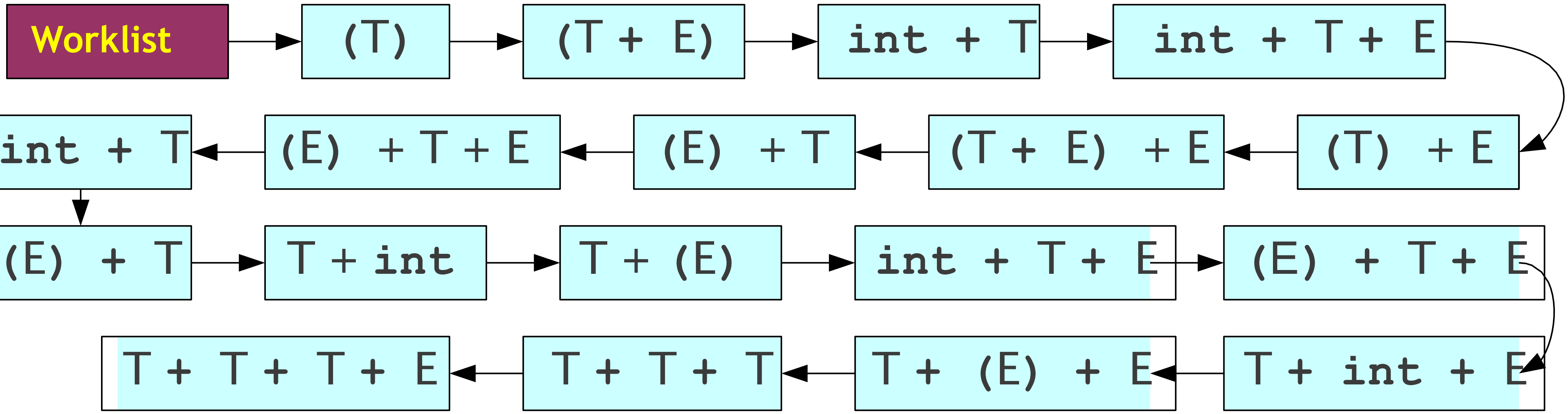

Worklist

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int + T

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T + int

T + (E)

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(E) + T + E

T + int + E

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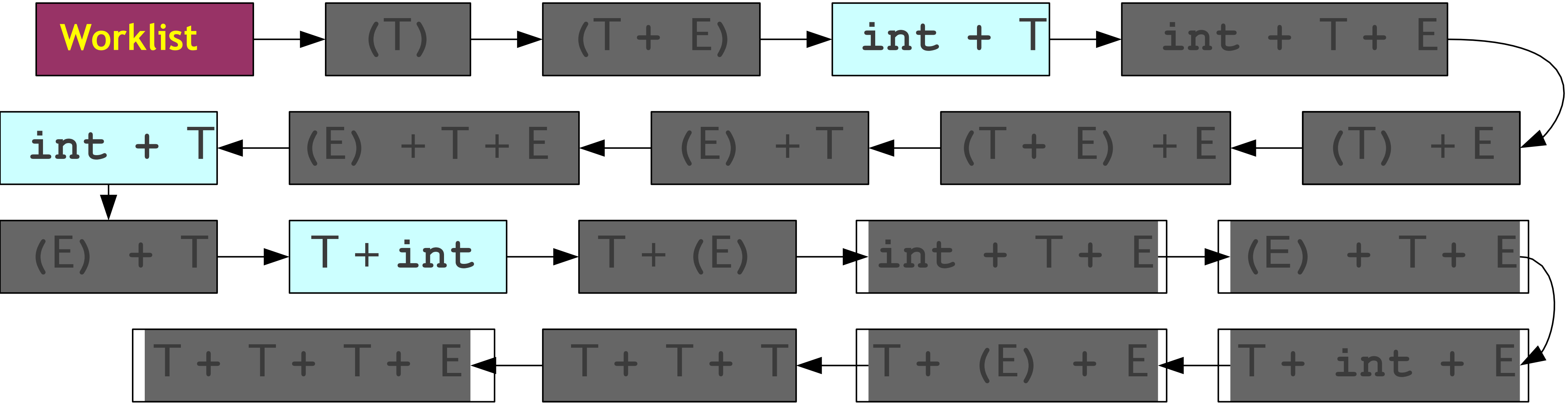


E → T

E → T + E

T → int

T → (E)

int + int

BFS is Slow

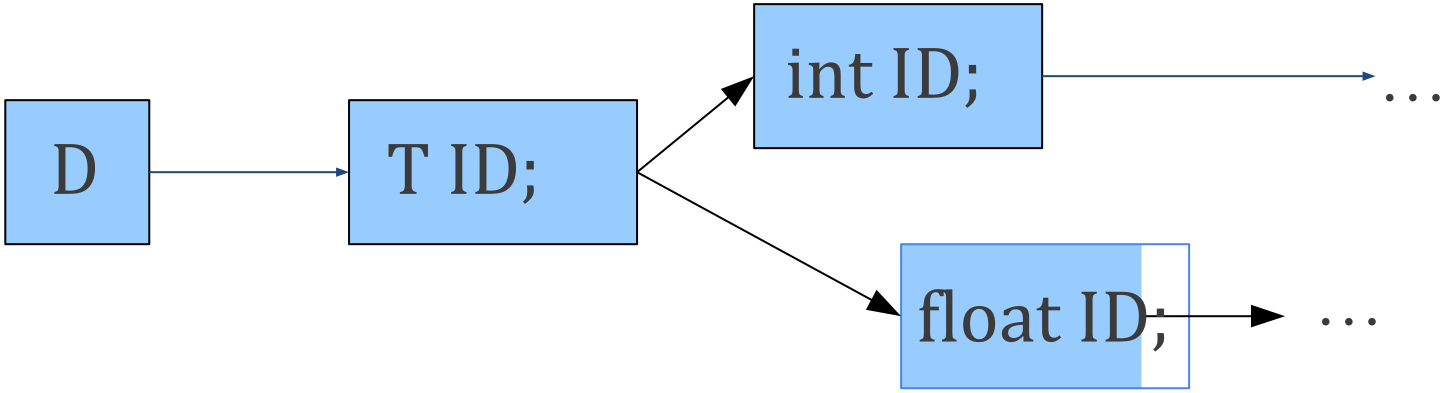
- Enormous time and memory usage:
  - Lots of **wasted effort**:
    - Generates a lot of sentential forms that couldn't possibly match.
    - But in general, extremely hard to tell whether a sentential form can match – that's the job of parsing!
  - High **branching factor**:
    - Each sentential form can expand in (potentially) many ways for each nonterminal it contains.

Reducing Wasted Effort

D → T ID;

T -> int | float

float abc;



Reducing Wasted Effort

- Suppose we're trying to match a string γ.
- Suppose we have a sentential form $\tau = \alpha\omega$, where α is a string of terminals and ω is a string of terminals and nonterminals.
- If α isn't a prefix of γ, then no string derived from τ can ever match γ.
- If we can find a way to try to get a prefix of terminals at the front of our sentential forms, then we can start pruning out impossible options.

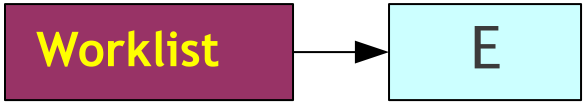
Reducing the Branching Factor

- If a string has many nonterminals in it, the branching factor can be high.
  - Sum of the number of productions of each nonterminal involved.
- If we can restrict which productions we apply, we can keep the branching factor lower.

Leftmost Derivations

- Recall: A **leftmost derivation** is one where we always expand the leftmost symbol first.
- Updated algorithm:
  - Do a breadth-first search, **only considering leftmost derivations**.
    - Dramatically drops branching factor.
    - Increases likelihood that we get a prefix of nonterminals.
  - Prune sentential forms that can't possibly match.
    - Avoids wasted effort.

Leftmost BFS



E → T

E → T + E

T → int

T → (E)

int + int

Leftmost BFS

Worklist

E

E → T

E → T + E

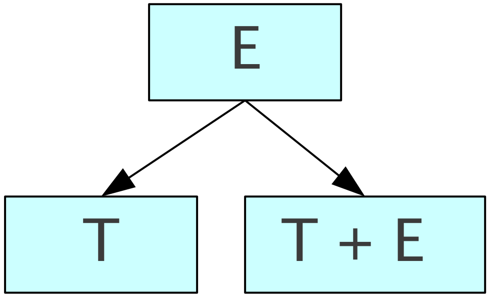
T → int

T → (E)

int + int

Leftmost BFS

Worklist



E → T

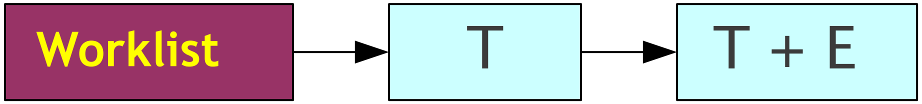
E → T + E

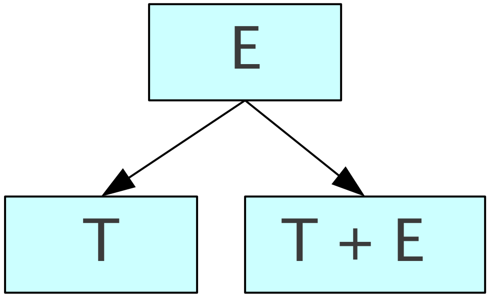
T → int

T → (E)

int + int

Leftmost BFS





E → T

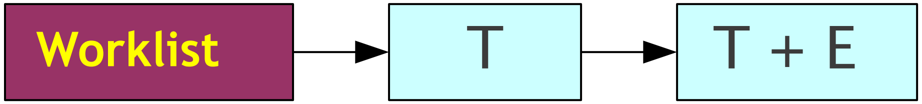
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



Worklist → T → T + E

E → T

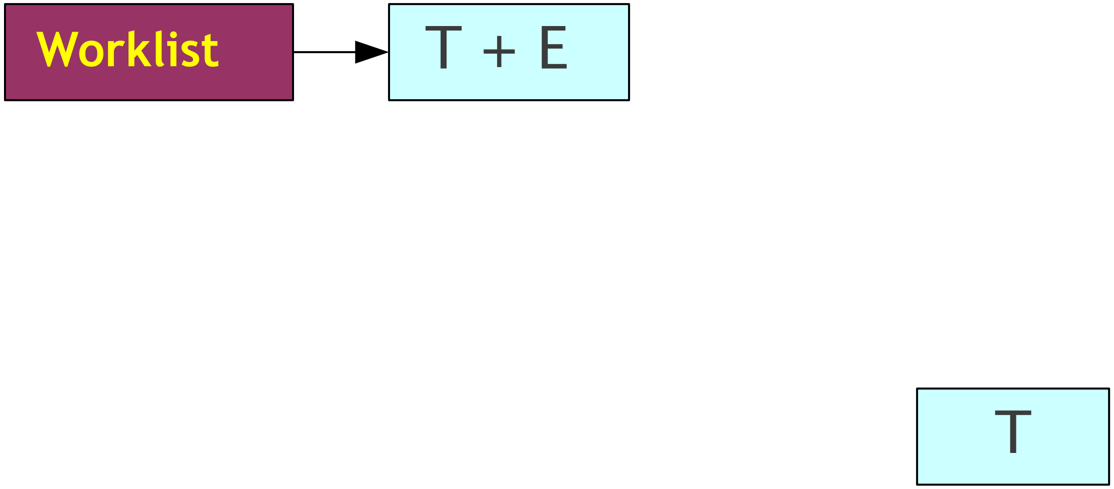
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

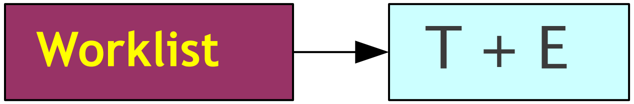
E → T + E

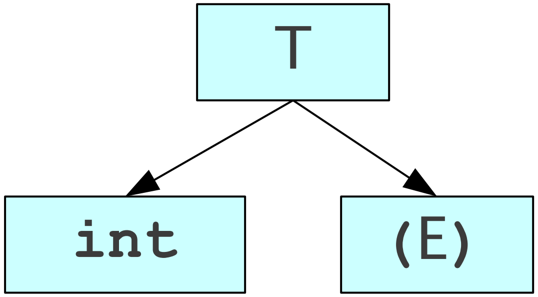
T → int

T → (E)

int + int

Leftmost BFS





E → T

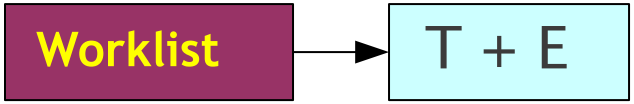
E → T + E

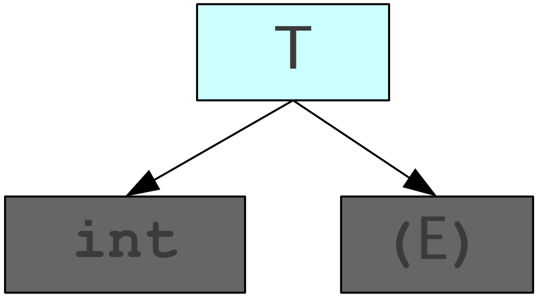
T → int

T → (E)

int + int

Leftmost BFS





E → T

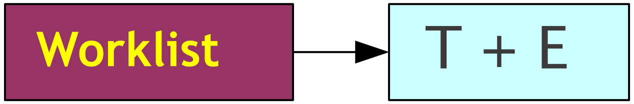
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



Worklist

T + E

E → T

E → T + E

T → int

T → (E)

int + int

Leftmost BFS

Worklist

T + E

E → T

E → T + E

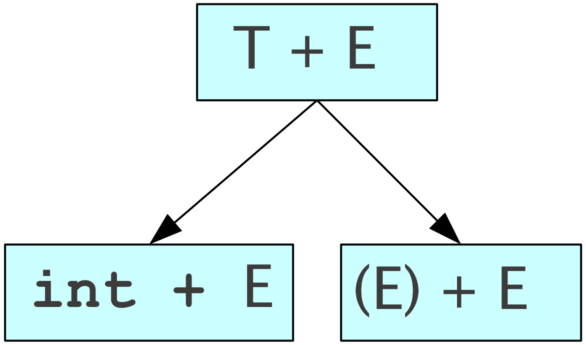
T → int

T → (E)

```
int + int
```

Leftmost BFS

Worklist



T + E

int + E

(E) + E

E → T

E → T + E

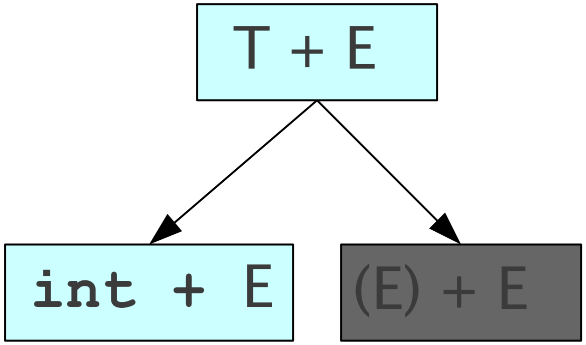
T → int

T → (E)

`int + int`

Leftmost BFS

Worklist



E → T

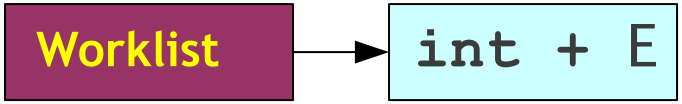
E → T + E

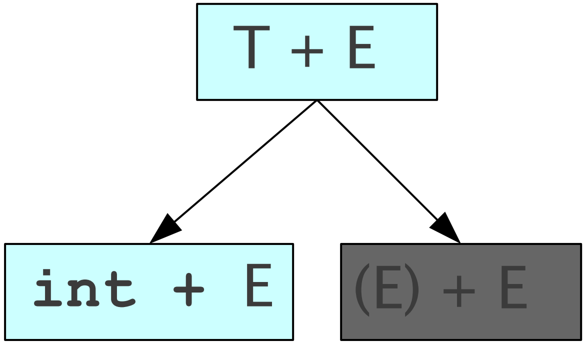
T → int

T → (E)

int + int

Leftmost BFS





E → T

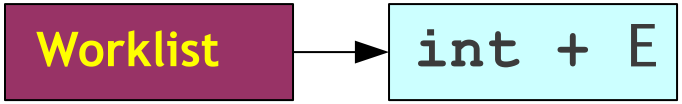
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

E → T + E

T → int

T → (E)

int + int

Leftmost BFS

Worklist

int + E

E → T

E → T + E

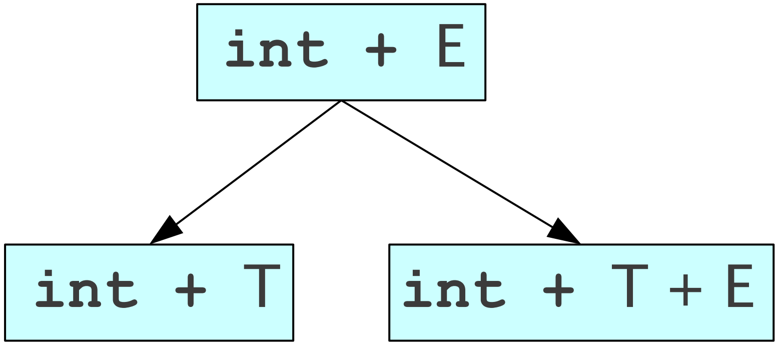
T → int

T → (E)

int + int

Leftmost BFS

Worklist



E → T

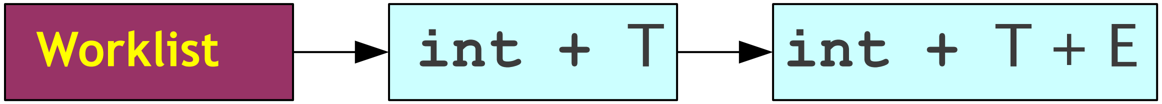
E → T + E

T → int

T → (E)

int + int

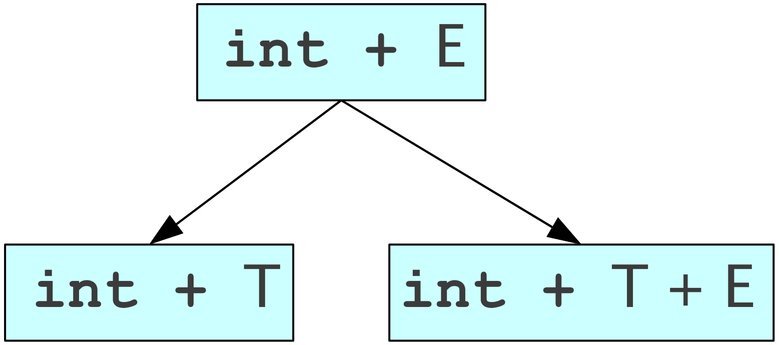
Leftmost BFS



Worklist

int + T

int + T + E



int + E

int + T

int + T + E

E → T

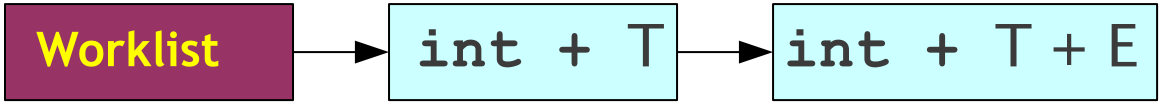
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



Worklist

int + T

int + T + E

E → T

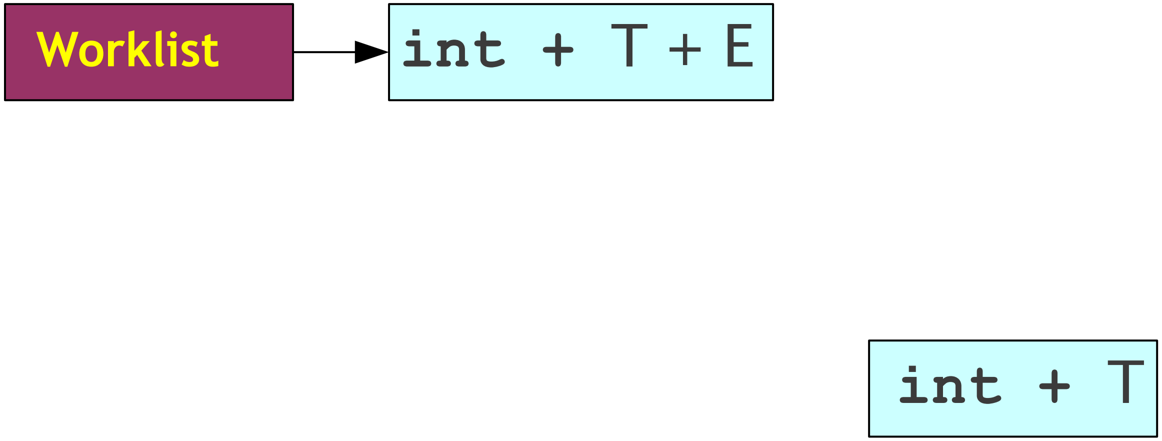
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

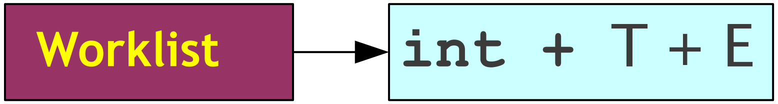
E → T + E

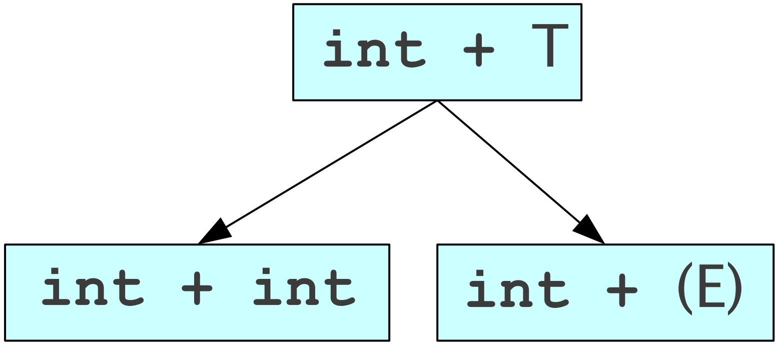
T → int

T → (E)

int + int

Leftmost BFS





E → T

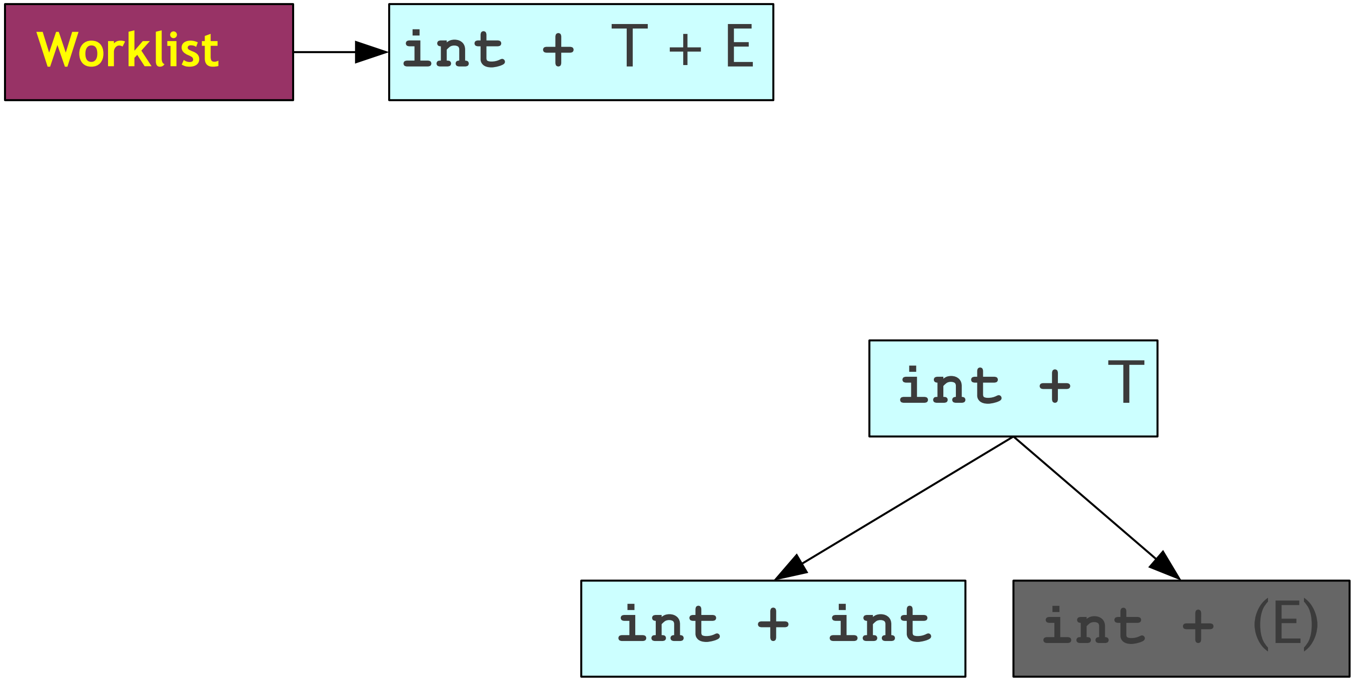
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

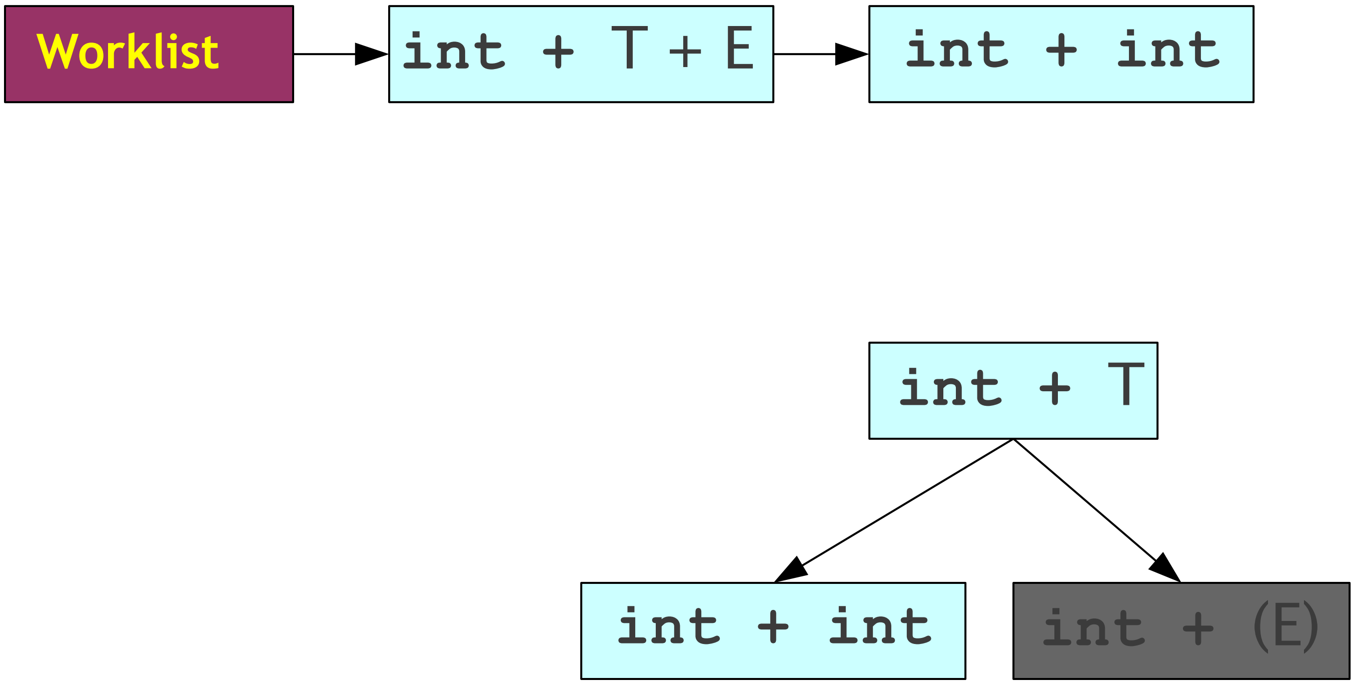
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

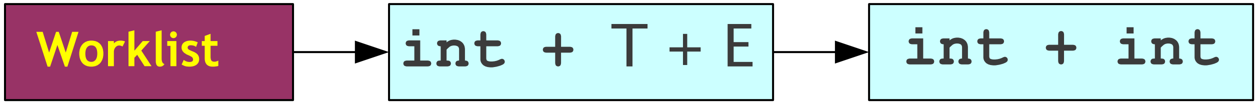
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



E → T

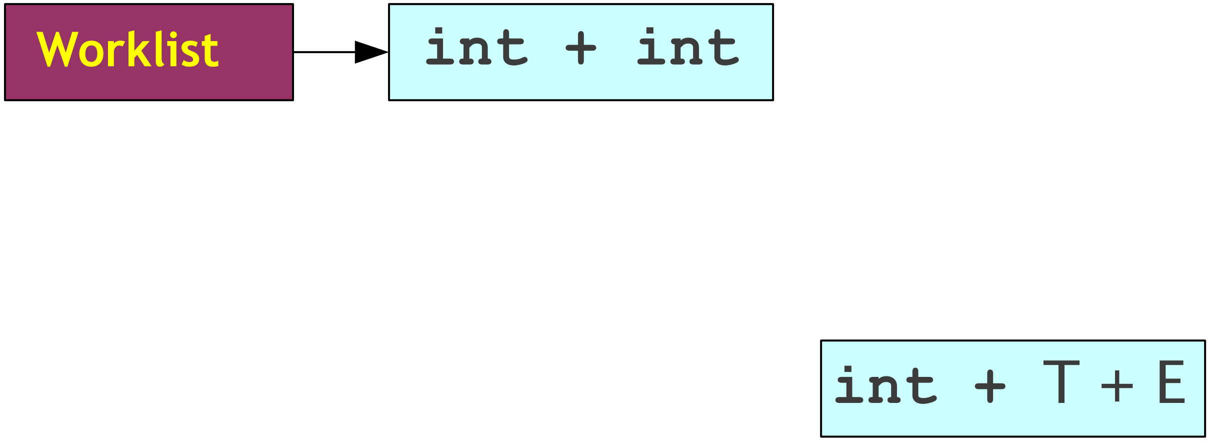
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



Worklist

int + int

int + T + E

E → T

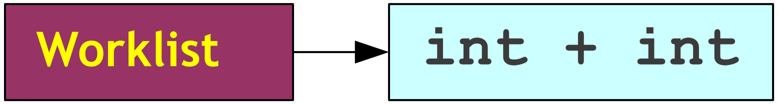
E → T + E

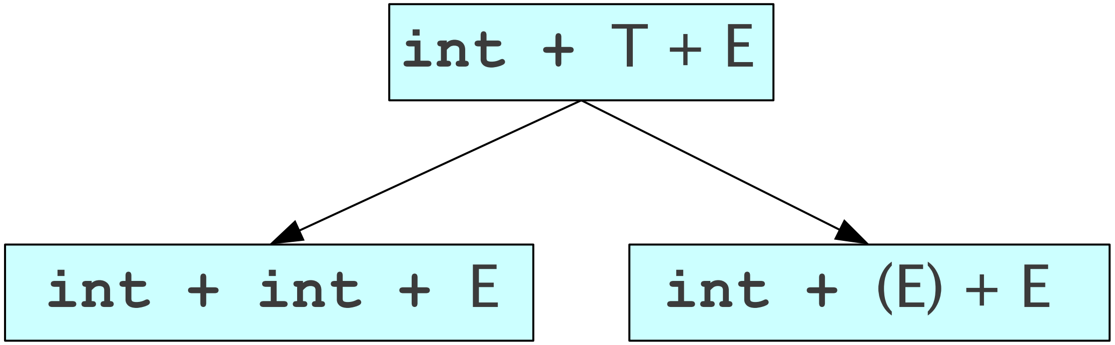
T → int

T → (E)

int + int

Leftmost BFS





E → T

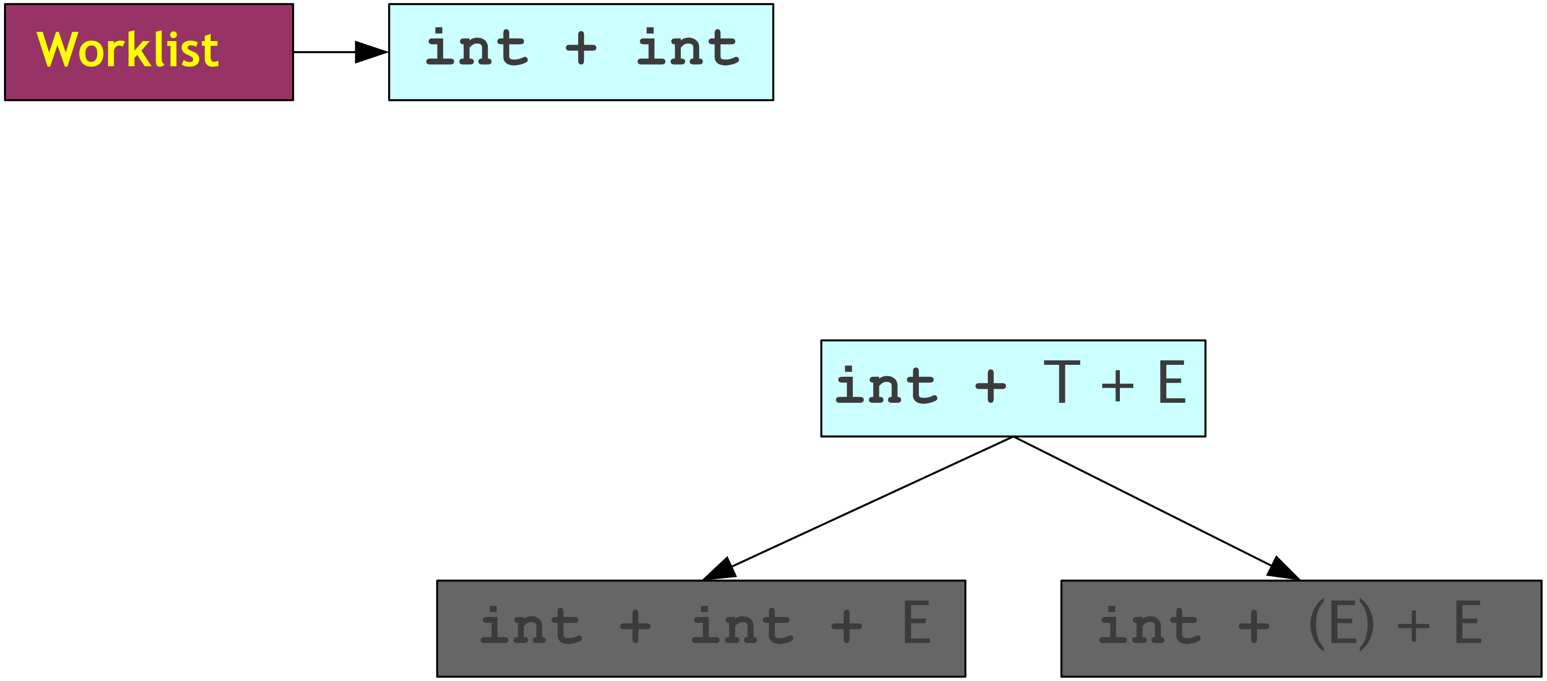
E → T + E

T → int

T → (E)

int + int

Leftmost BFS



Worklist

int + int

int + T + E

int + int + E

int + (E) + E

E → T

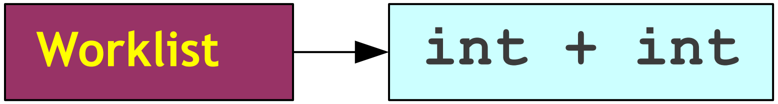
E → T + E

T → int

T → (E)

int + int

Leftmost BFS


Worklist

int + int

E → T

E → T + E

T → int

T → (E)

int + int

Leftmost BFS

Worklist

`int + int`

$E \to T$

$E \to T + E$

$T \to$ `int`

$T \to$ `(E)`

`int + int`

Leftmost BFS

- Substantial improvement over naïve algorithm.
- Will always find a valid parse of a program if one exists.
- But, there are still problems.

Leftmost BFS Has Problems

Worklist

$A \rightarrow Aa \mid Ab \mid c$

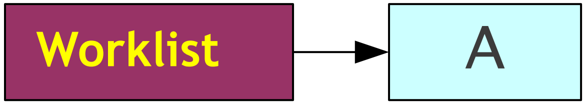
Leftmost BFS Has Problems

Worklist

A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems



A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems

Worklist

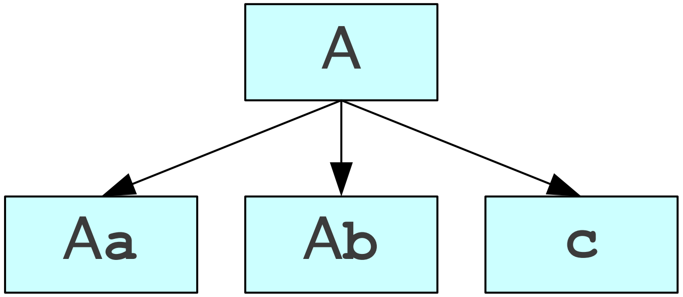
A

A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems

Worklist

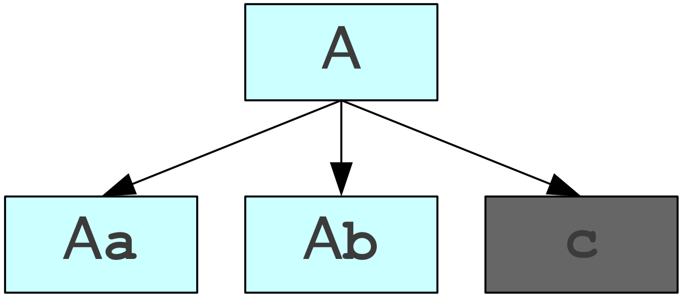


A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems

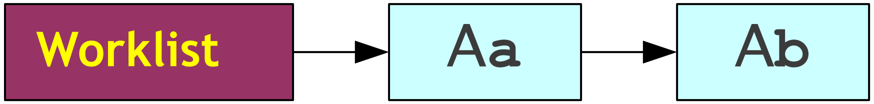
Worklist

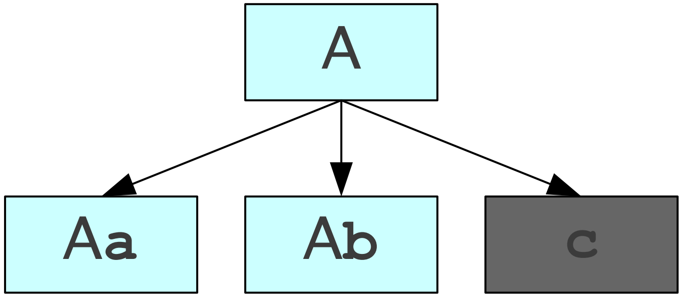


A → Aa | Ab | c

caaaaaaaaaa

Leftmost BFS Has Problems

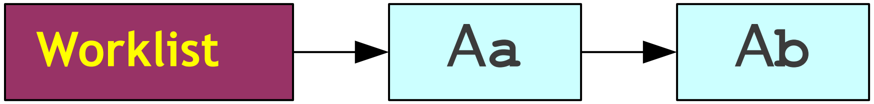




A → Aa | Ab | c

caaaaaaaaaa

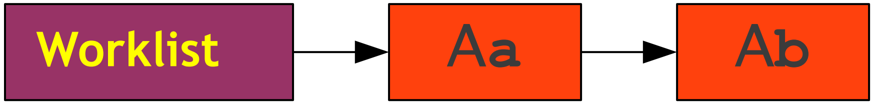
Leftmost BFS Has Problems



A → Aa | Ab | c

caaaaaaaaaa

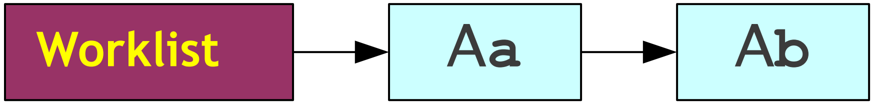
Leftmost BFS Has Problems



A → Aa | Ab | c

caaaaaaaaaa

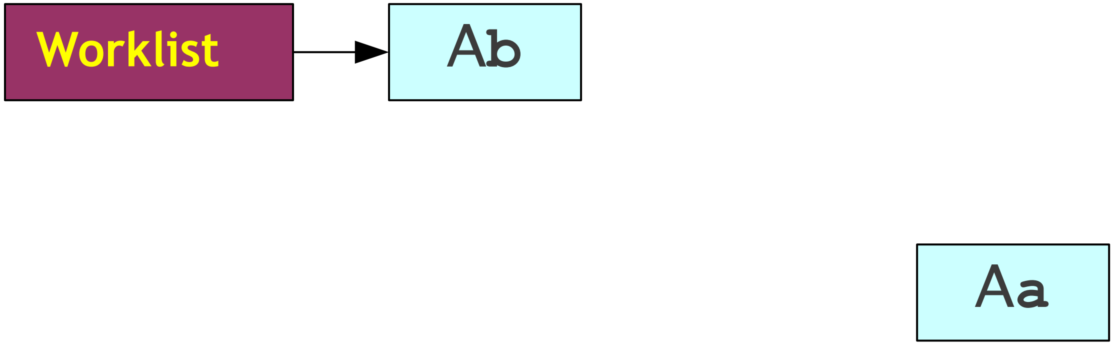
Leftmost BFS Has Problems



A → Aa | Ab | c

caaaaaaaaaa

Leftmost BFS Has Problems



Worklist

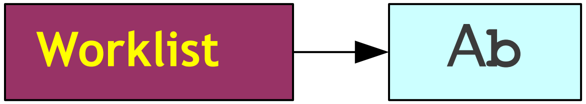
Ab

Aa

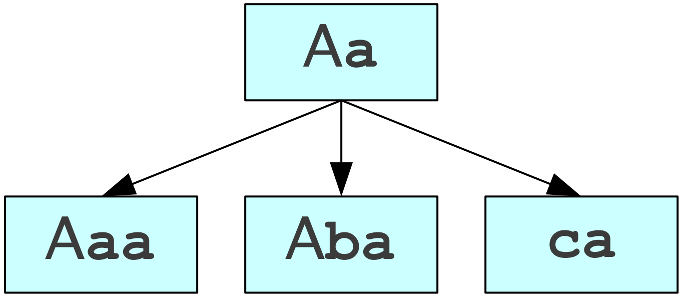
A → Aa | Ab | c

caaaaaaaaaa

Leftmost BFS Has Problems


Worklist

Ab


Aa

Aaa

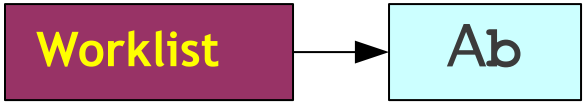
Aba

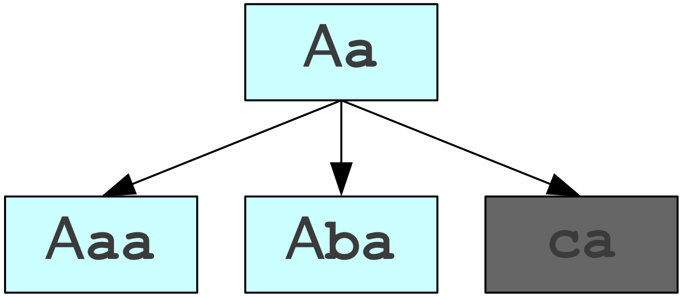
ca

A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems

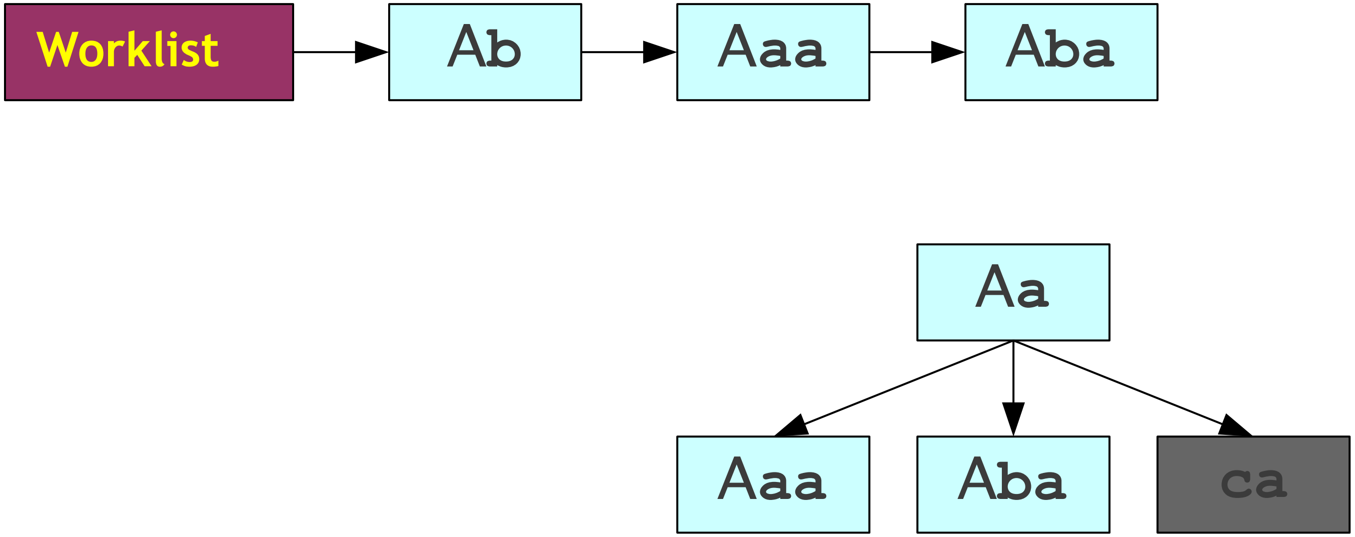




A → Aa | Ab | c

caaaaaaaaa

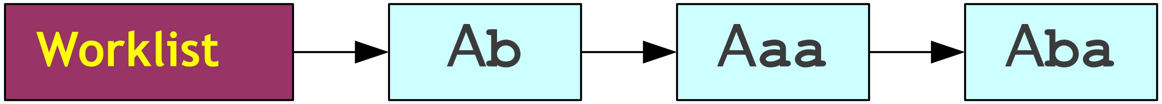
Leftmost BFS Has Problems



A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems



Worklist

Ab

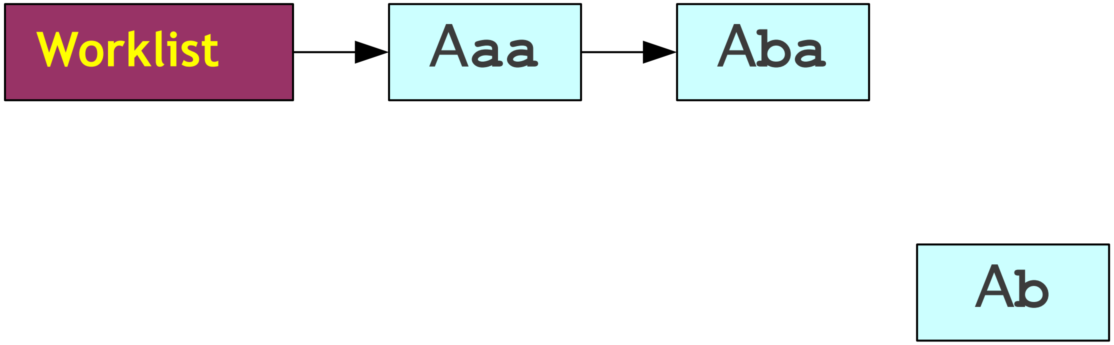
Aaa

Aba

A → Aa | Ab |
c

caaaaaaaaaa

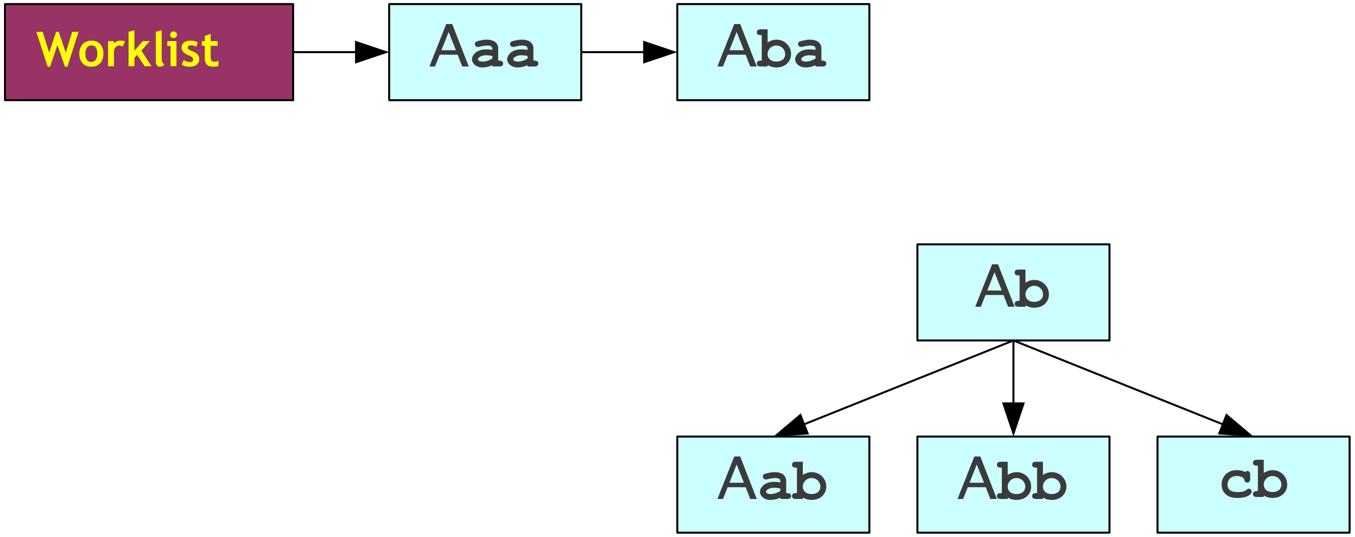
Leftmost BFS Has Problems



A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems



Worklist

Aaa

Aba

Ab

Aab

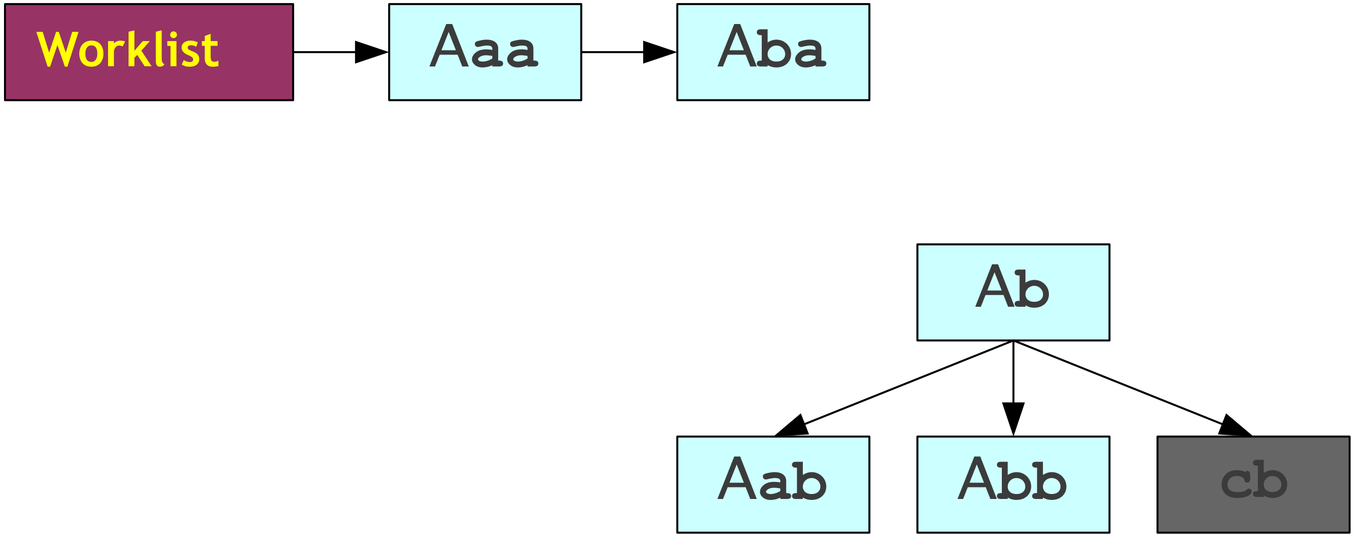
Abb

cb

A → Aa | Ab |
c

caaaaaaaaaa

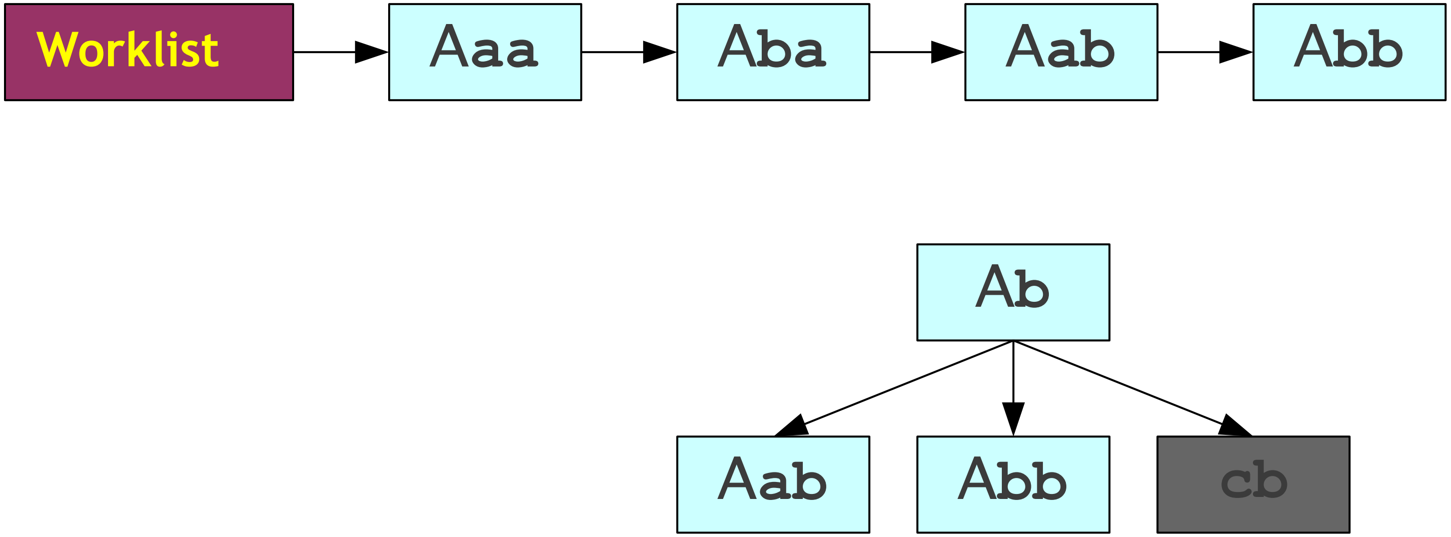
Leftmost BFS Has Problems



A → Aa | Ab | c

caaaaaaaaa

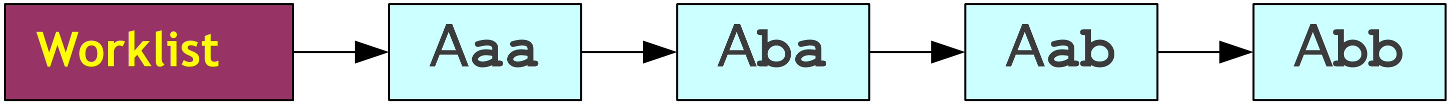
Leftmost BFS Has Problems



A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems



Worklist

Aaa

Aba

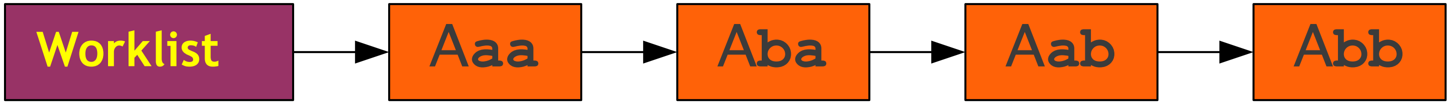
Aab

Abb

A → Aa | Ab |
c

caaaaaaaaaa

Leftmost BFS Has Problems



A → Aa | Ab |
c

caaaaaaaaaa

Problems with Leftmost BFS

- Grammars like this can make parsing take exponential time.
- Also uses exponential memory.
- What if we search the graph with a different algorithm?

Leftmost DFS

- Idea: Use **depth-first** search.
- Advantages:
  - Lower memory usage: Only considers one branch at a time.
  - High performance: On many grammars, runs very quickly.
  - Easy to implement: Can be written as a set of mutually recursive functions.

Leftmost DFS

$E \rightarrow T$

$E \rightarrow T+ E$

$T \rightarrow int$

$T \rightarrow (E)$

Leftmost DFS

$$E \rightarrow T$$

$$E \rightarrow T + E$$

$$T \rightarrow \texttt{int}$$

$$T \rightarrow (E)$$

`int + int`

Leftmost DFS

E

E → T

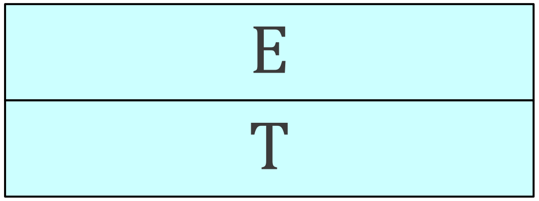
E → T+ E

T → int

T → (E)

```
int + int
```

Leftmost DFS



E → T

E → T+ E

T → int

T → (E)

int + int

Leftmost DFS

E
T
`int`

E → T

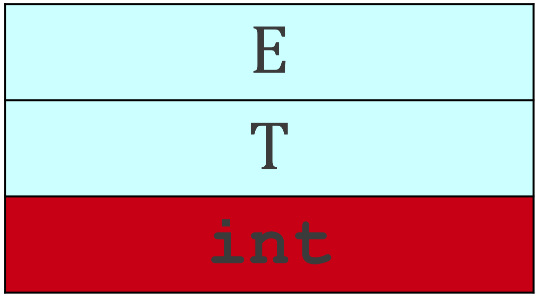
E → T`+` E

T → `int`

T → `(`E`)`

`int + int`

Leftmost DFS


E

T

int

E → T

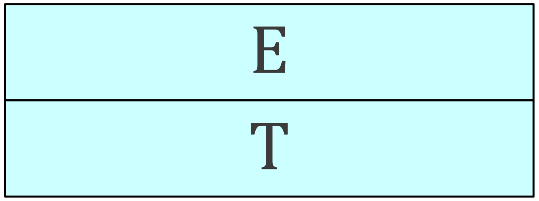
E → T+ E

T → int

T → (E)

```
int + int
```

Leftmost DFS



E

T

E → T

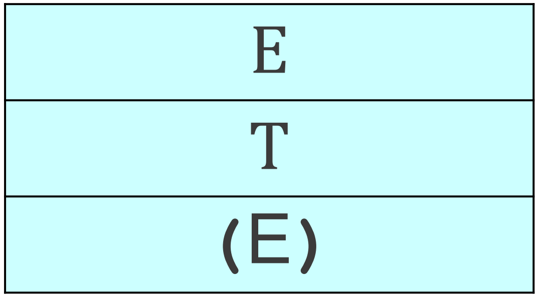
E → T+ E

T → int

T → (E)

int + int

Leftmost DFS



E

T

(E)

E → T

E → T+ E

T → int

T → (E)

int + int

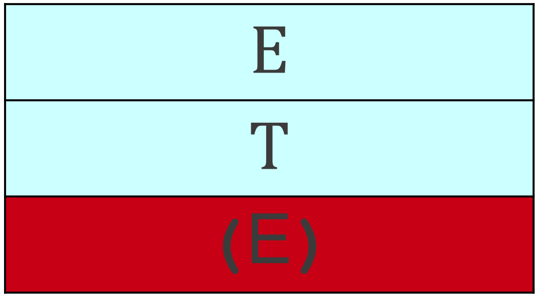
Leftmost DFS

E → T

E → T+ E

T → int

T → (E)



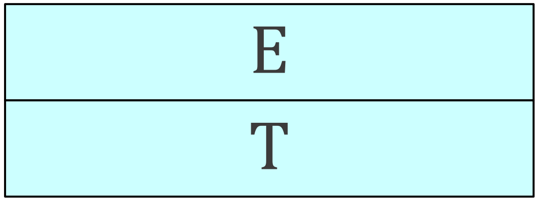
E

T

(E)

int + int

Leftmost DFS


E

T

E → T

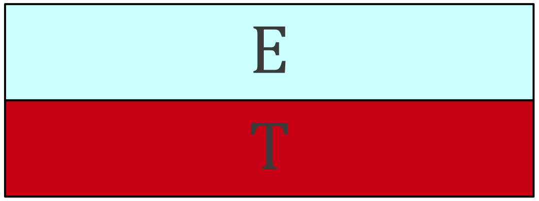
E → T+ E

T → int

T → (E)

`int + int`

Leftmost DFS



E

T

E → T

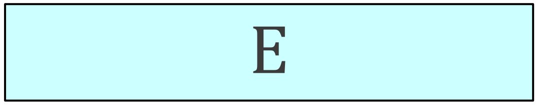
E → T+ E

T → int

T → (E)

```
int + int
```

Leftmost DFS



E → T

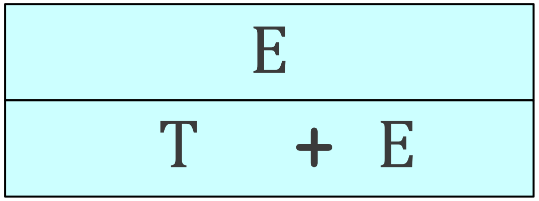
E → T+ E

T → int

T → (E)

```
int + int
```

Leftmost DFS



E

T + E

E → T

E → T+ E

T → int

T → (E)

int + int

Leftmost DFS

E → T

E → T+ E

T → int

T → (E)

E
T + E
int + E

int + int

Leftmost DFS

E → T

E → T+ E

T → int

T → (E)

E
T + E
int + E
int + T

int + int

Leftmost DFS

E → T

E → T+ E

T → int

T → (E)

E
T + E
int + E
int + T
int + int

int + int

Summary of Leftmost BFS/DFS

- Worst-case runtime is exponential.
- Worst-case memory usage is exponential.

- Worst-case runtime is exponential.
- Worst-case memory usage is linear.

Predictive Parsing

Predictive Parsing

- The leftmost DFS/BFS algorithms are **backtracking** algorithms.
  - Guess which production to use, then back up if it doesn't work.
  - Try to match a prefix by sheer dumb luck.
- There is another class of parsing algorithms called **predictive** algorithms.
  - Based on remaining input, predict (*without backtracking*) which production to use.

Exploiting Lookahead

- Given just the start symbol, how do you know which productions to use to get to the input program?
- Idea: Use **lookahead tokens**.
- When trying to decide which production to use, look at some number of tokens of the input to help make the decision.

Predictive Parsing

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E
(E Op E)

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E
(E Op E)
(int Op E)

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E
(E Op E)
(int Op E)
(int + E)

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E
(E Op E)
(int Op E)
(int + E)
(int + (E Op E))

E → int

E → (E Op E)

Op → +

Op → *

(	int	+	(	int	*	int	)	)

Predictive Parsing

E → int

E → (E Op E)

Op → +

Op → *

E
(E Op E)
(int Op E)
(int + E)
(int + (E Op E))
(int + (int Op E))

(	int	+	(	int	*	int	)	)

Predictive Parsing

E → int
E → (E Op E)
Op → +
Op → *

E
(E Op E)
(int Op E)
(int + E)
(int + (E Op E))
(int + (int Op E))
(int + (int * E))

(	int	+	(	int	*	int	)	)

Predictive Parsing

E → int

E → (E Op E)

Op → +

Op → *

E
(E Op E)
(int Op E)
(int + E)
(int + (E Op E))
(int + (int Op E))
(int + (int * E))
(int + (int * int))

(	int	+	(	int	*	int	)	)

Predictive Parsing

E → int
E → (E Op E)
Op → +
Op → *

E
(E Op E)
(int Op E)
(int + E)
(int + (E Op E))
(int + (int Op E))
(int + (int * E))
(int + (int * int))

(	int	+	(	int	*	int	)	)

A Simple Predictive Parser: **LL(1)**

- Top-down, predictive parsing:
  - **L**: Left-to-right scan of the tokens
  - **L**: Leftmost derivation.
  - **(1)**: One token of lookahead
- Construct a leftmost derivation for the sequence of tokens.
- When expanding a nonterminal, we predict the production to use by looking at the next token of the input. **The decision is forced.**