Synthesizing Transformations on Hierarchically Structured Data

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THE UNIVERSITY OF TEXAS AT AUSTIN

RICE

Hierarchical Data Structures

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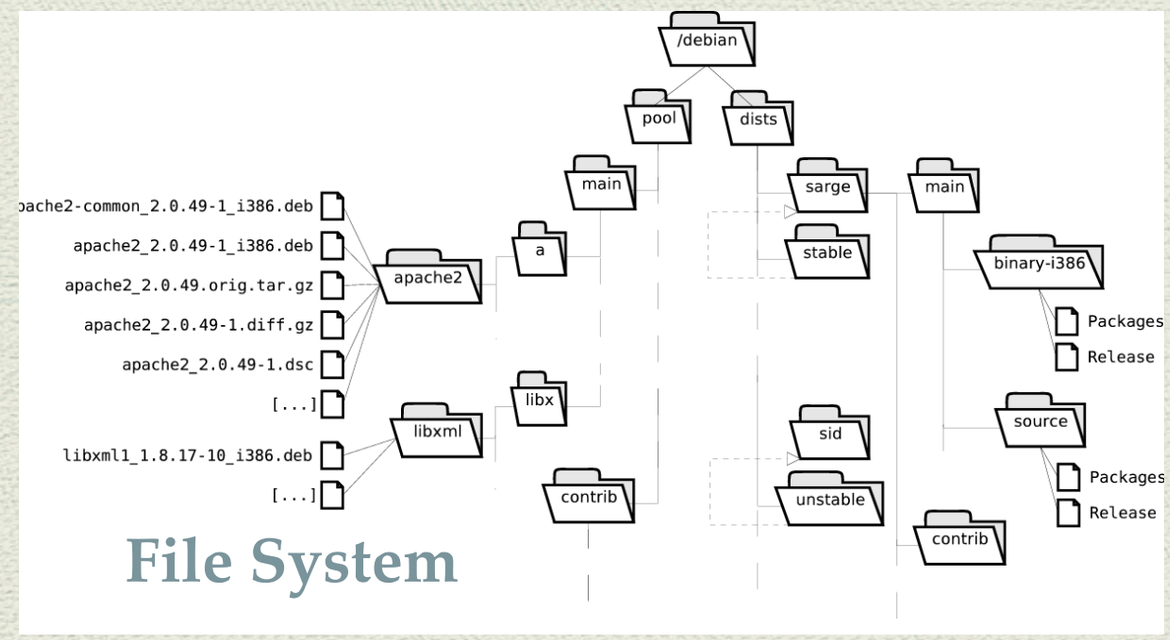

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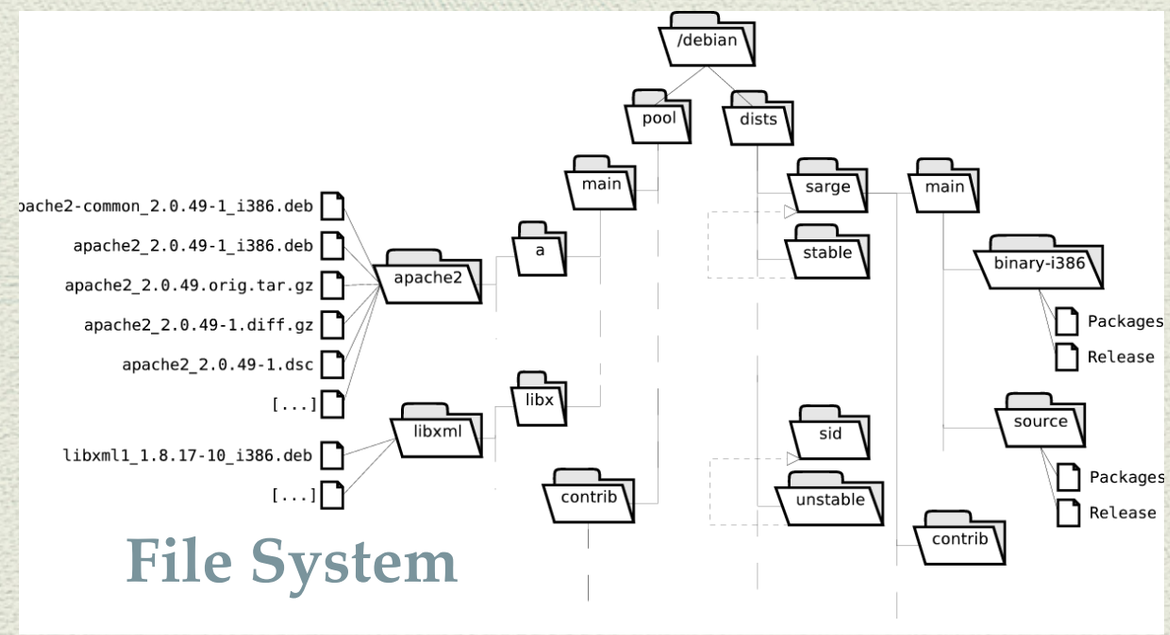

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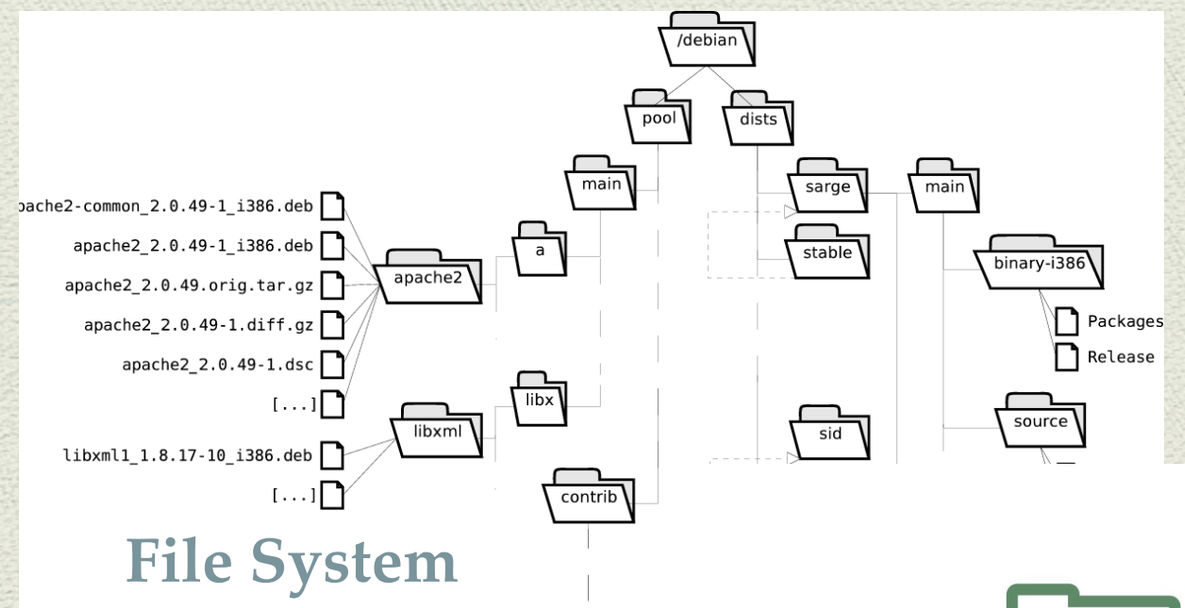

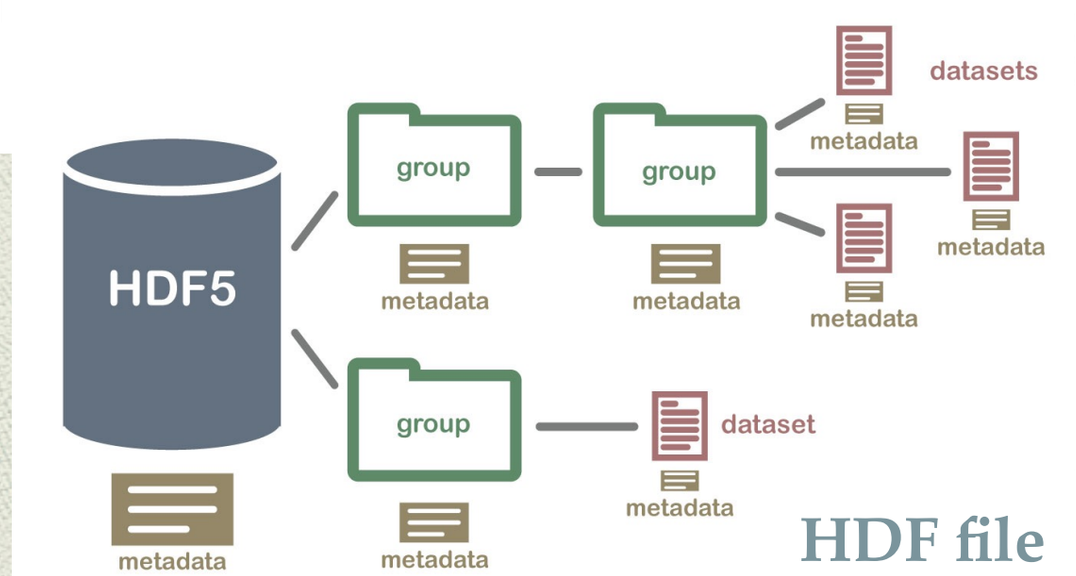

Hierarchical Data Structures

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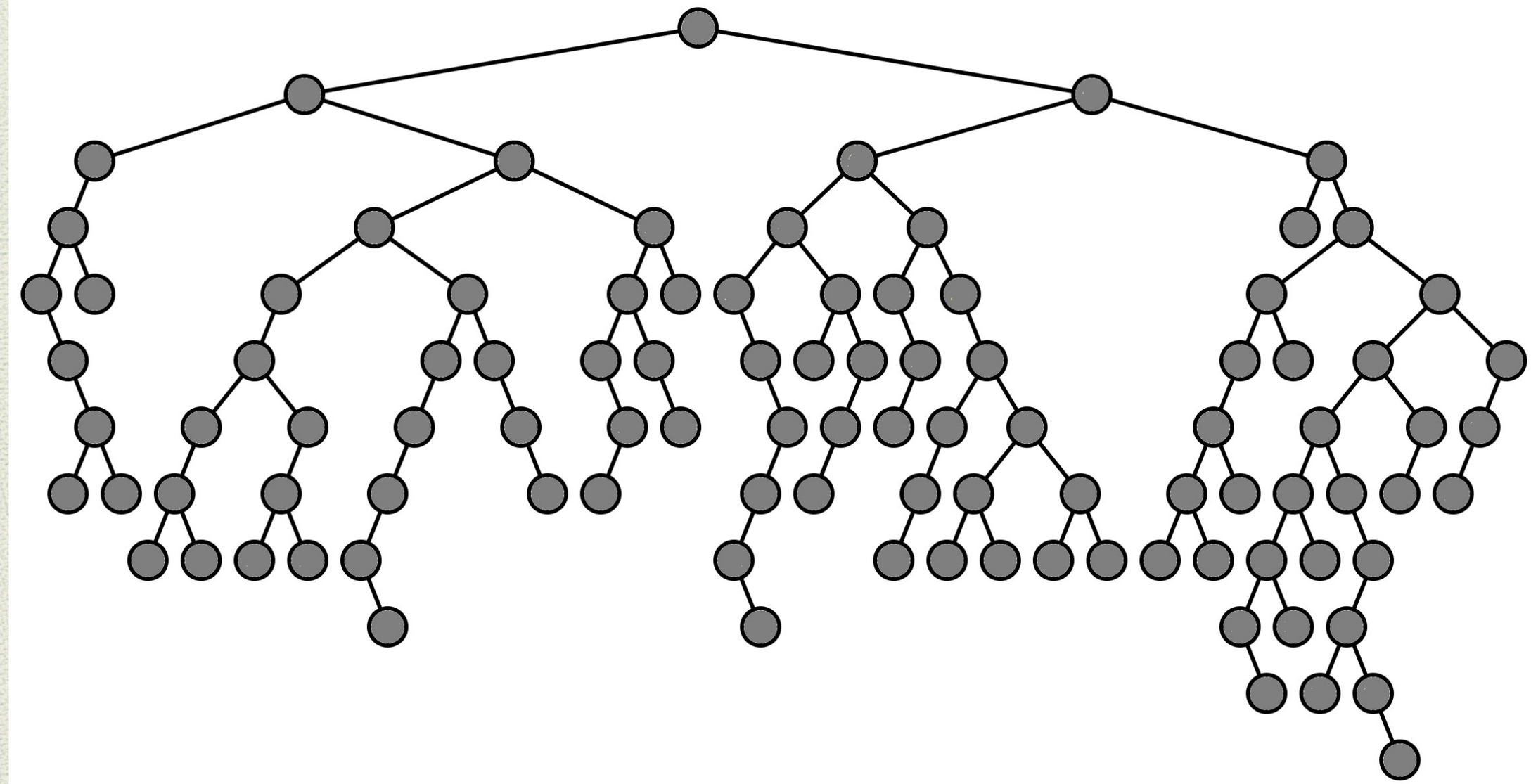
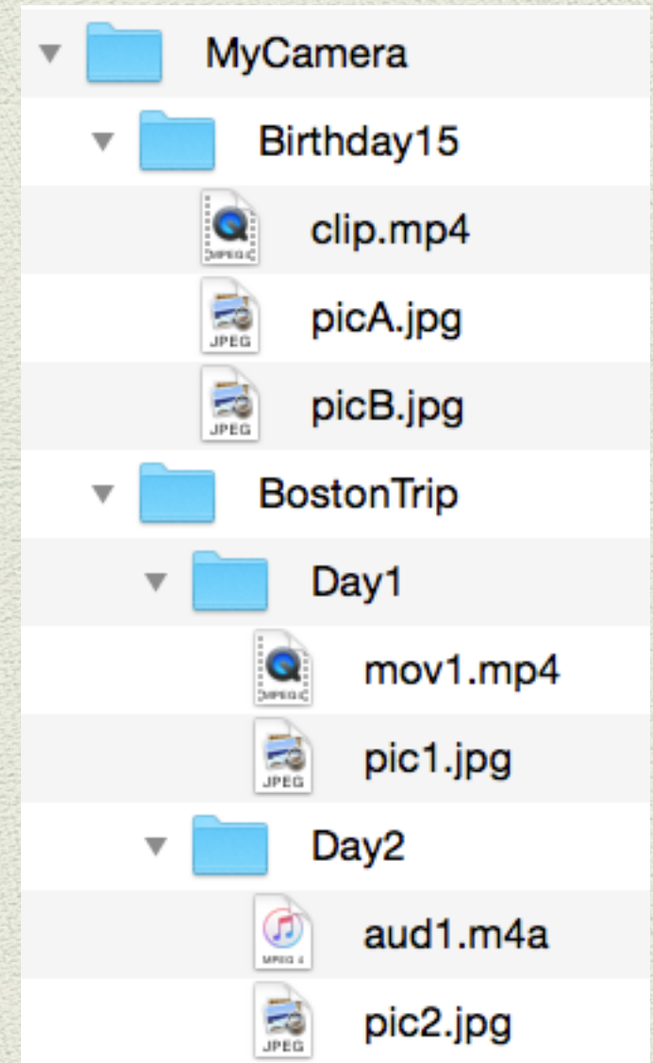
All of these structures are basically **Trees**.



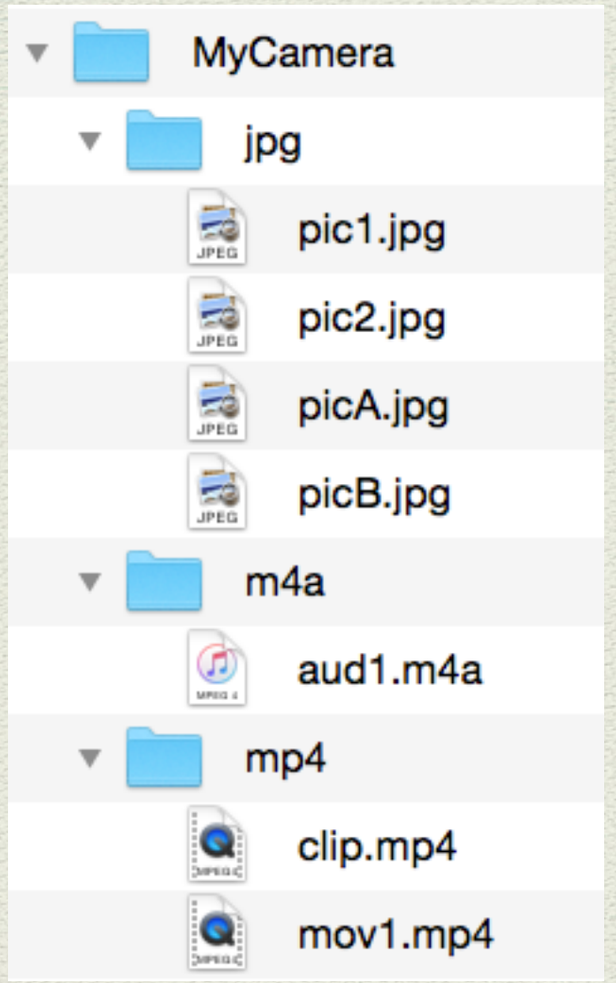
Tree Transformation

- Many user tasks require transforming the underlying tree.



Original Directory

Reorganize files based on their extensions



Modified Directory

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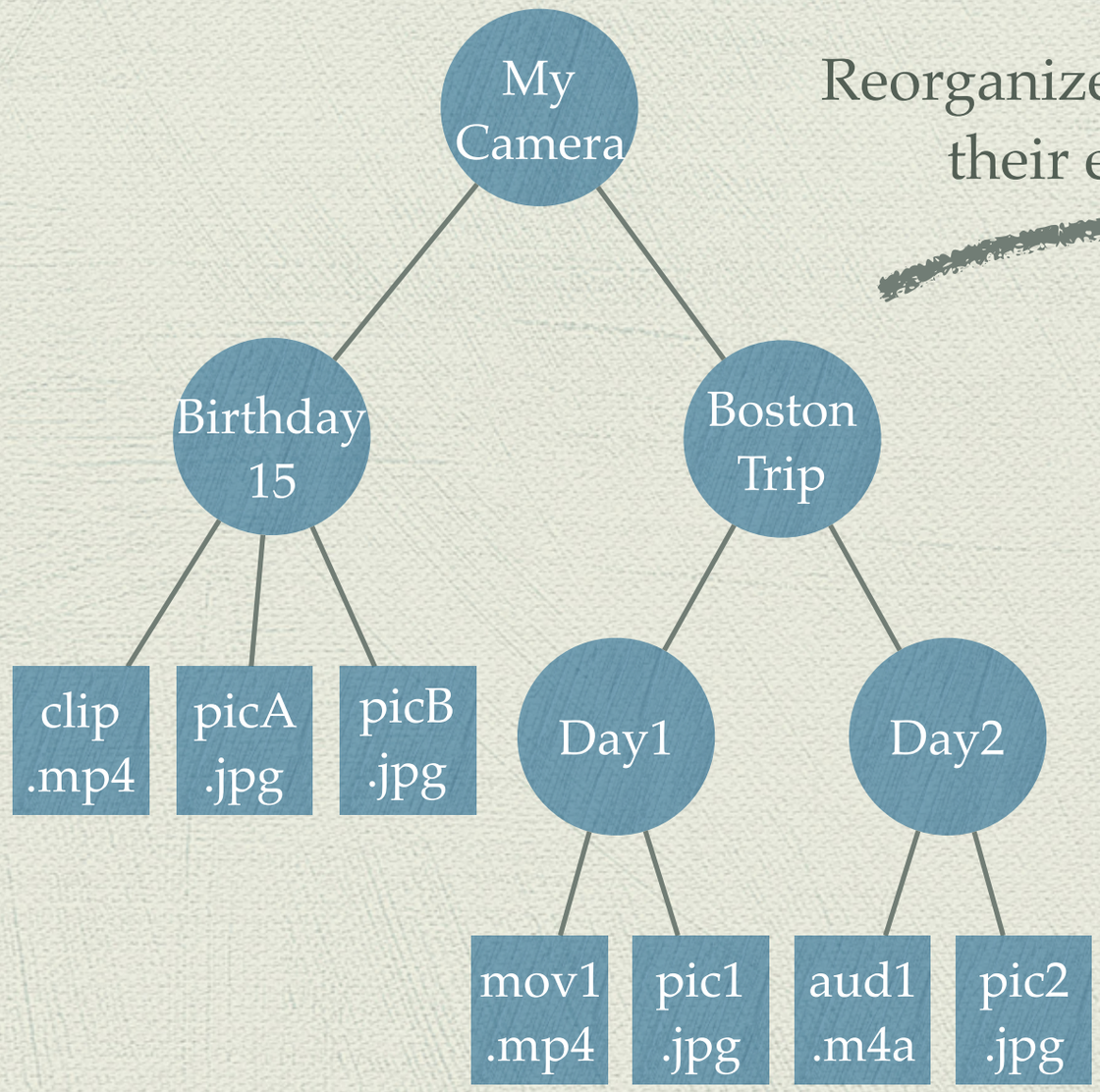

Original Tree

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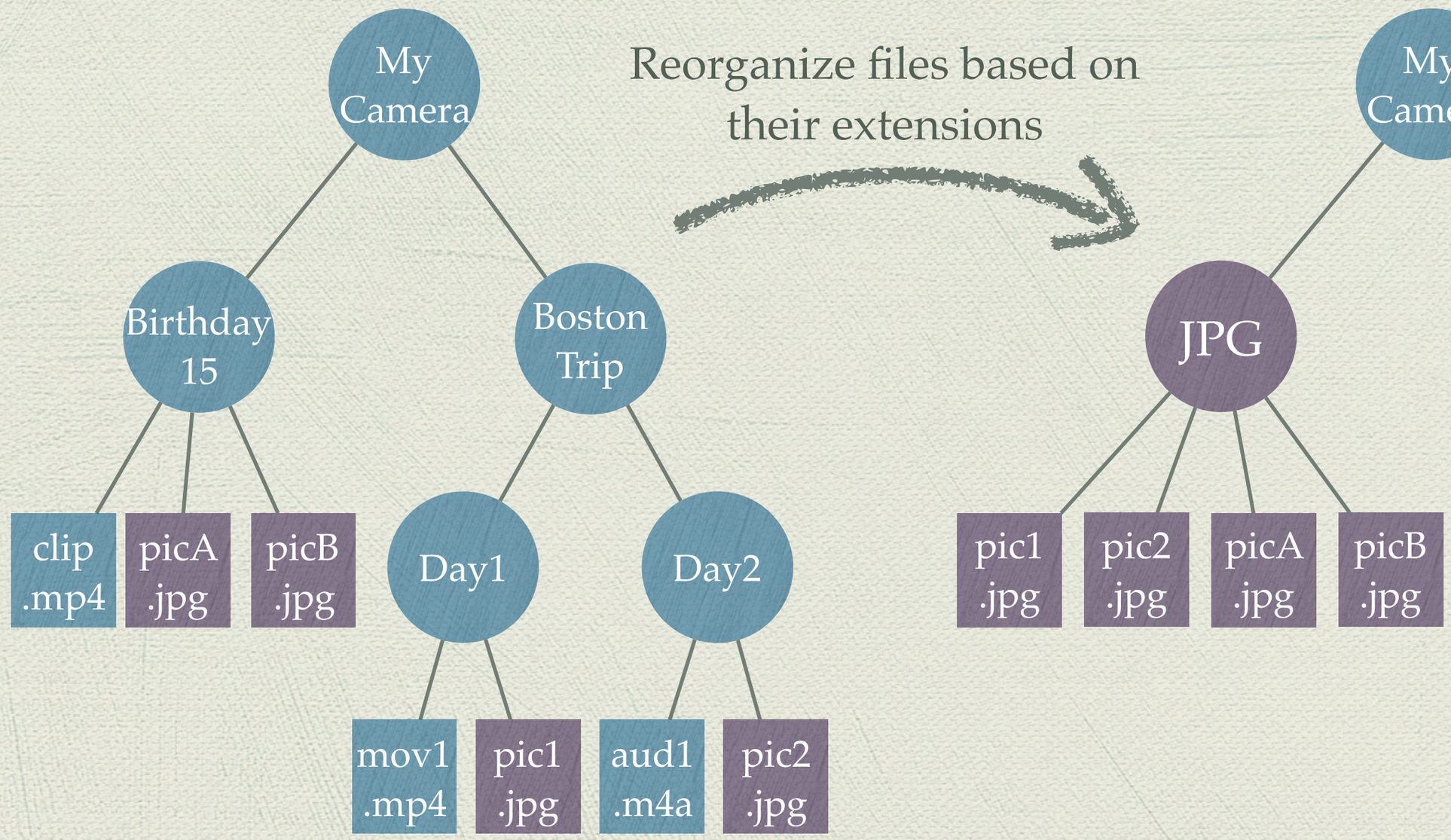

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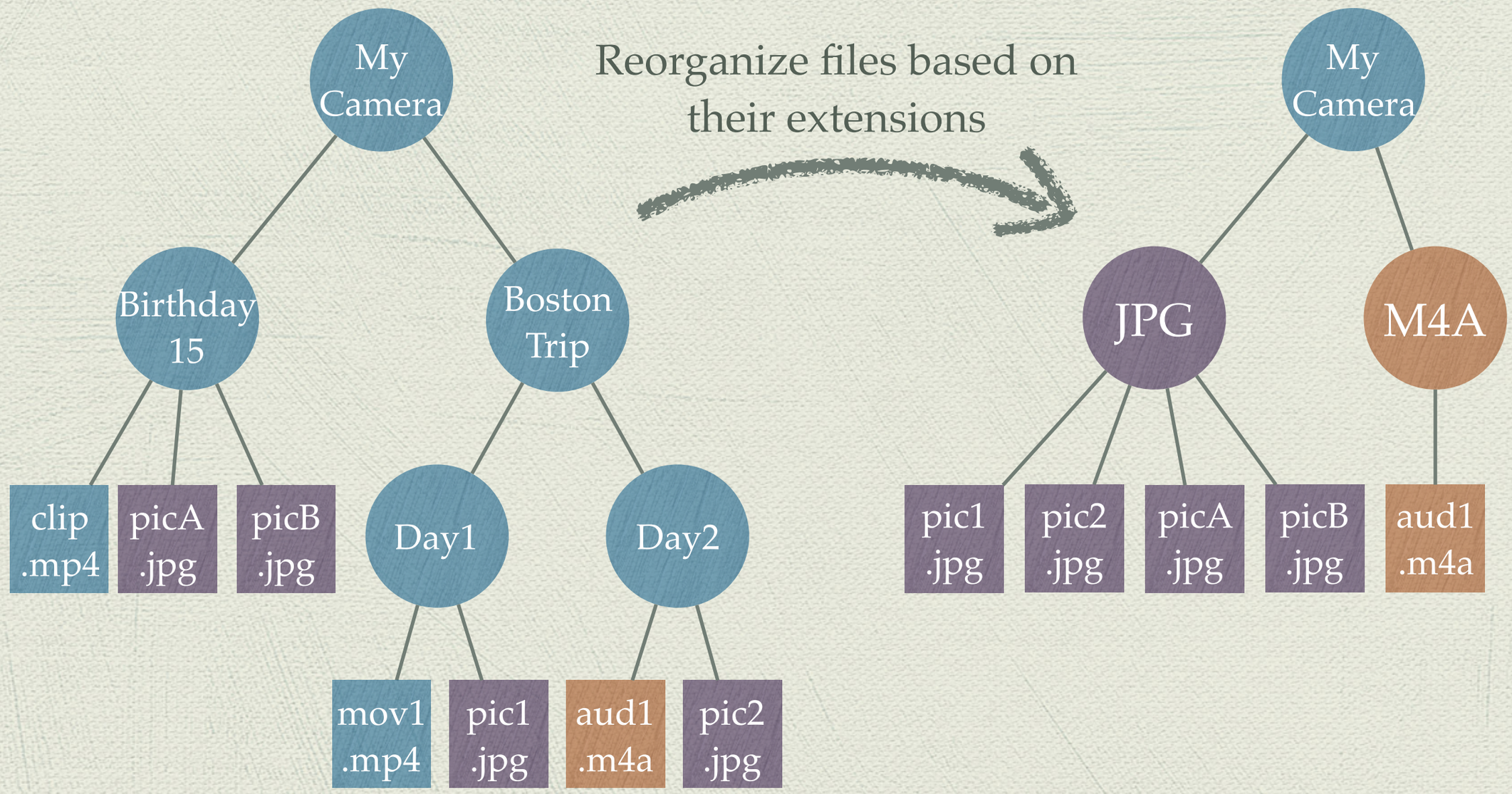

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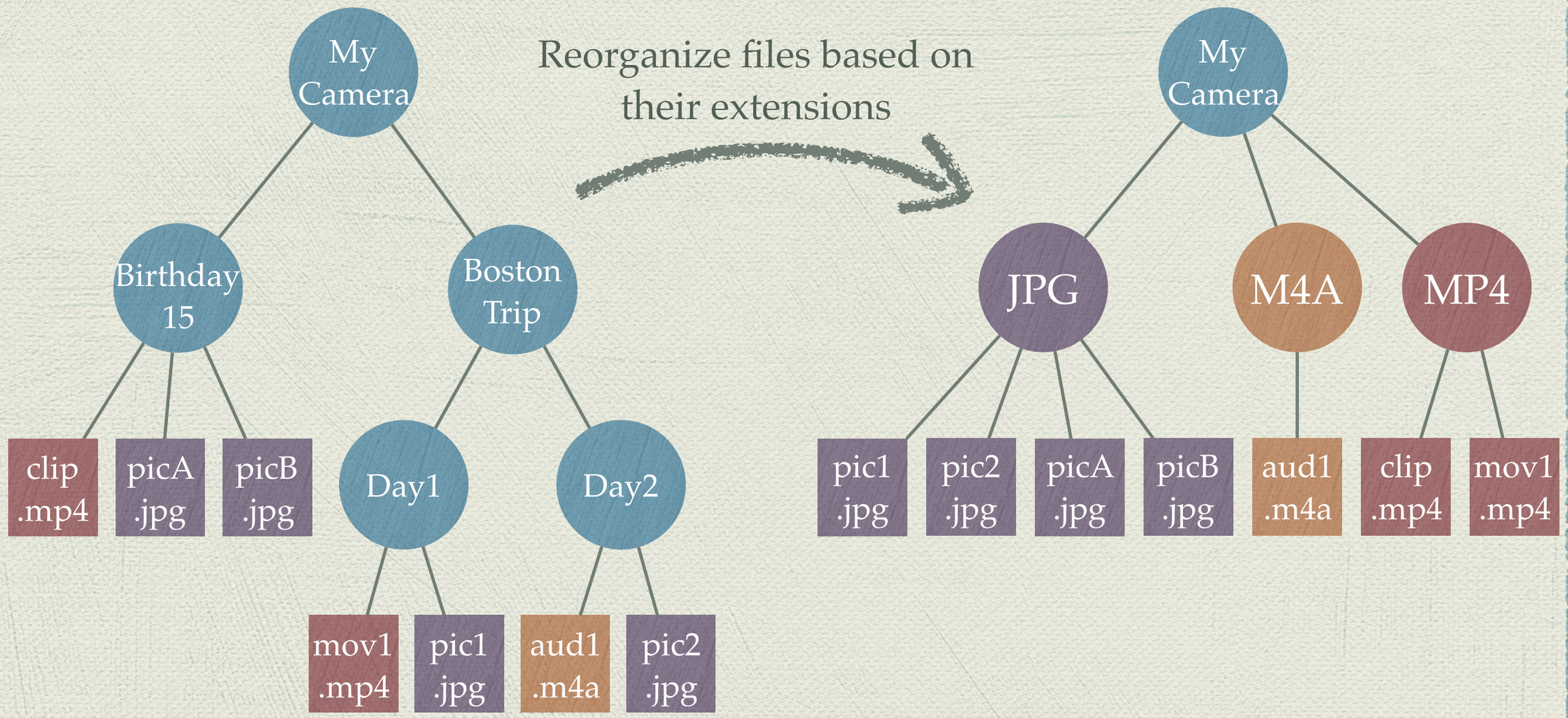

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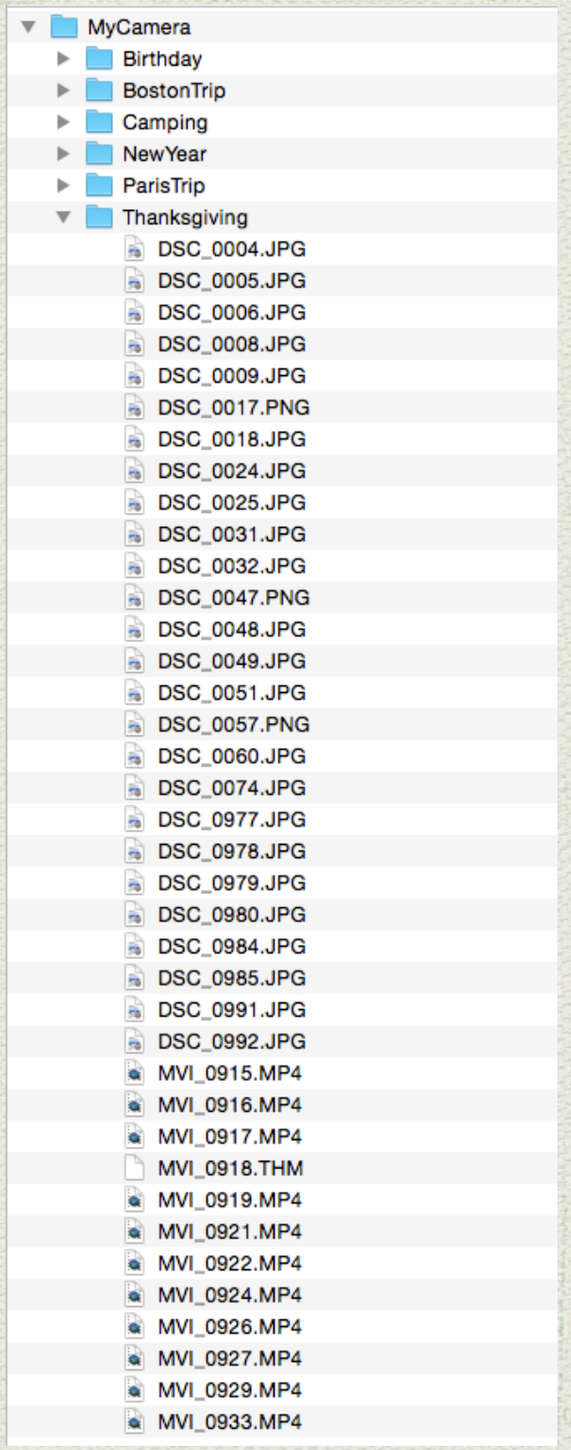

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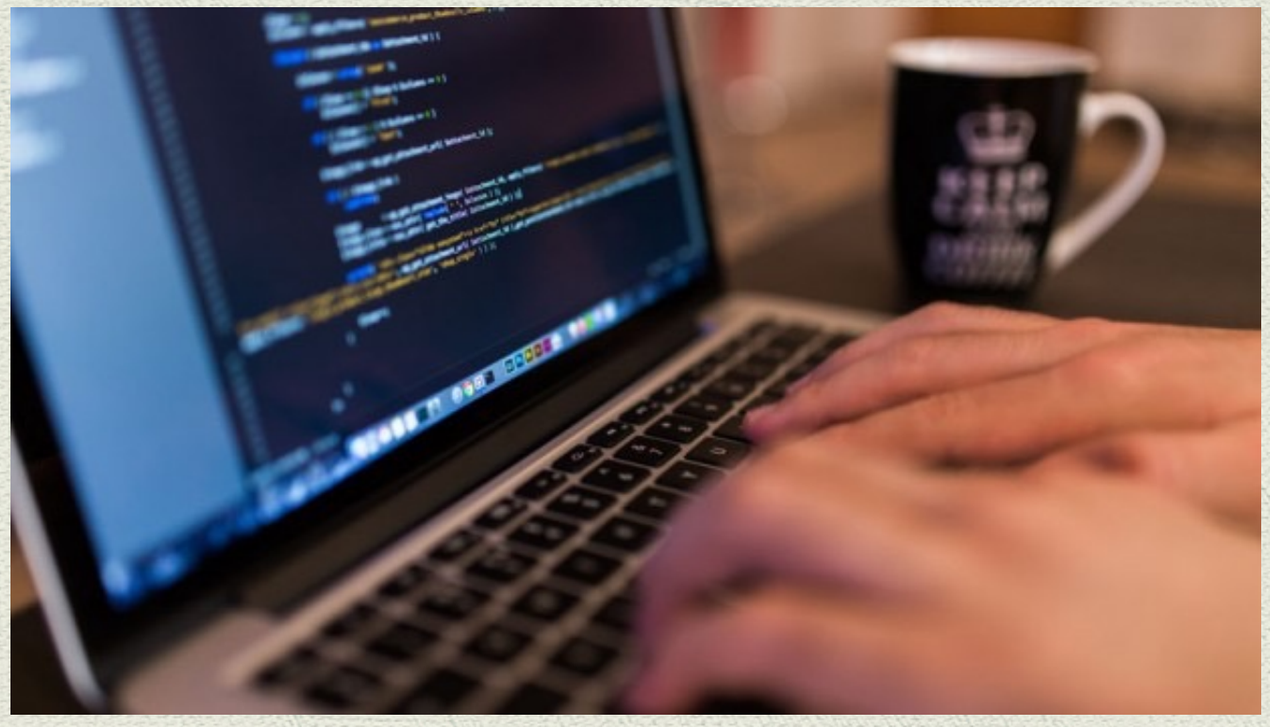

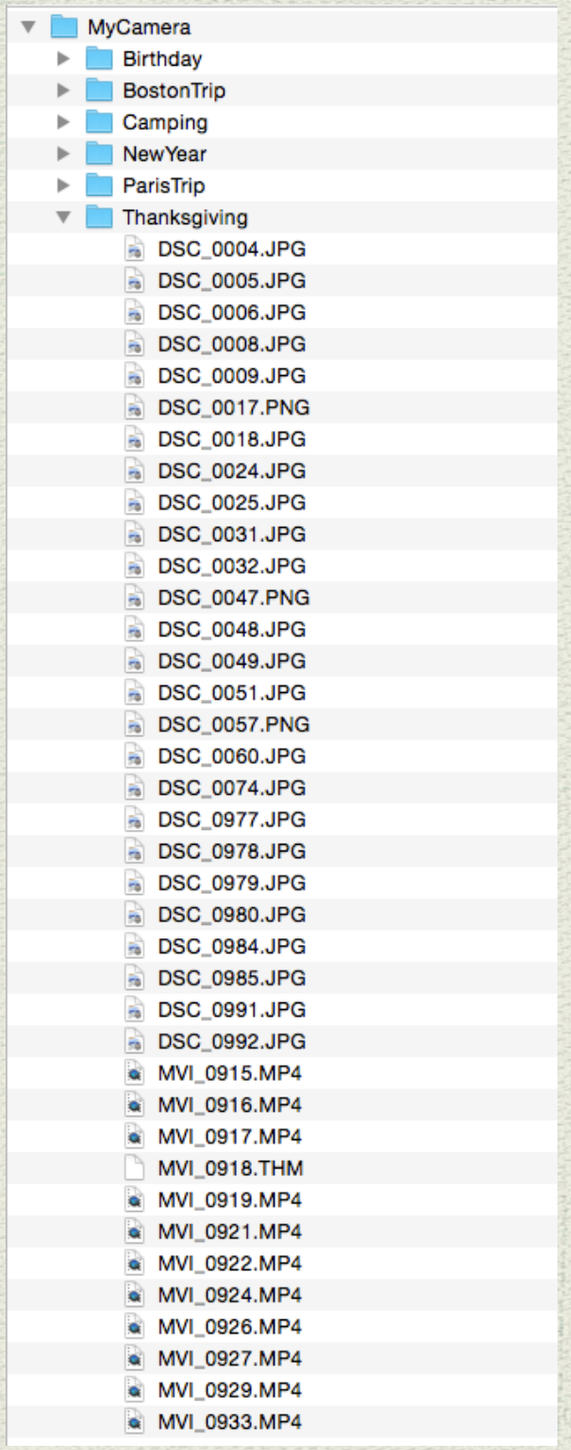

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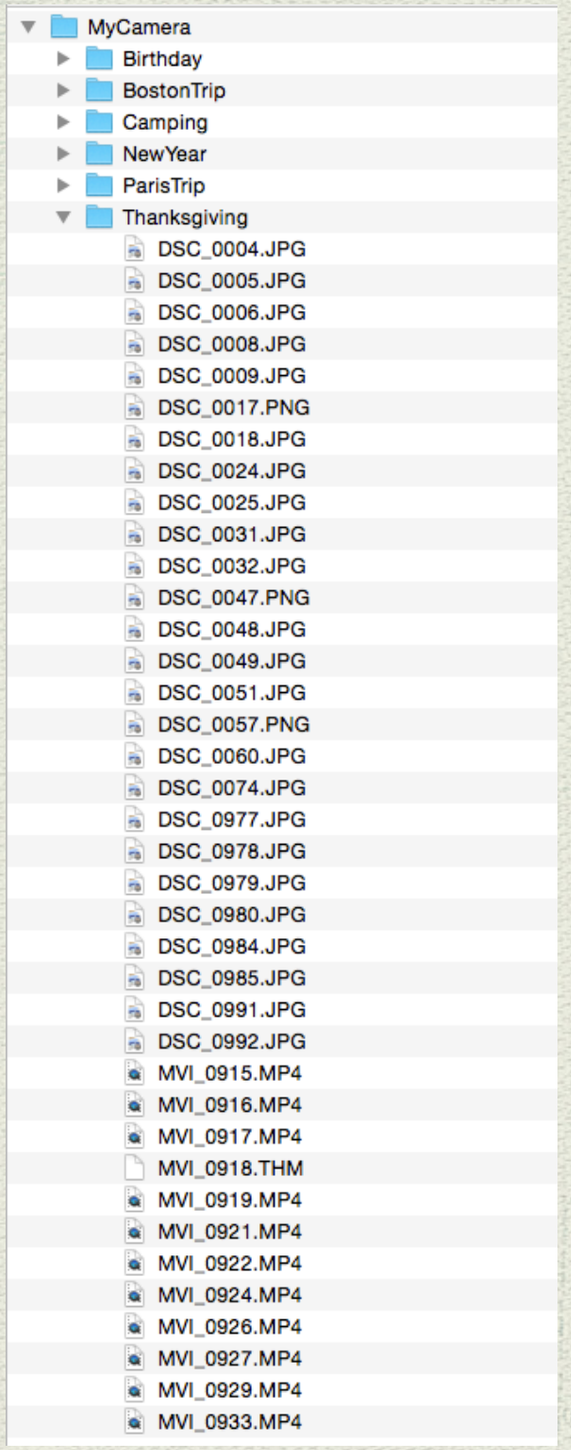

Need for Synthesis

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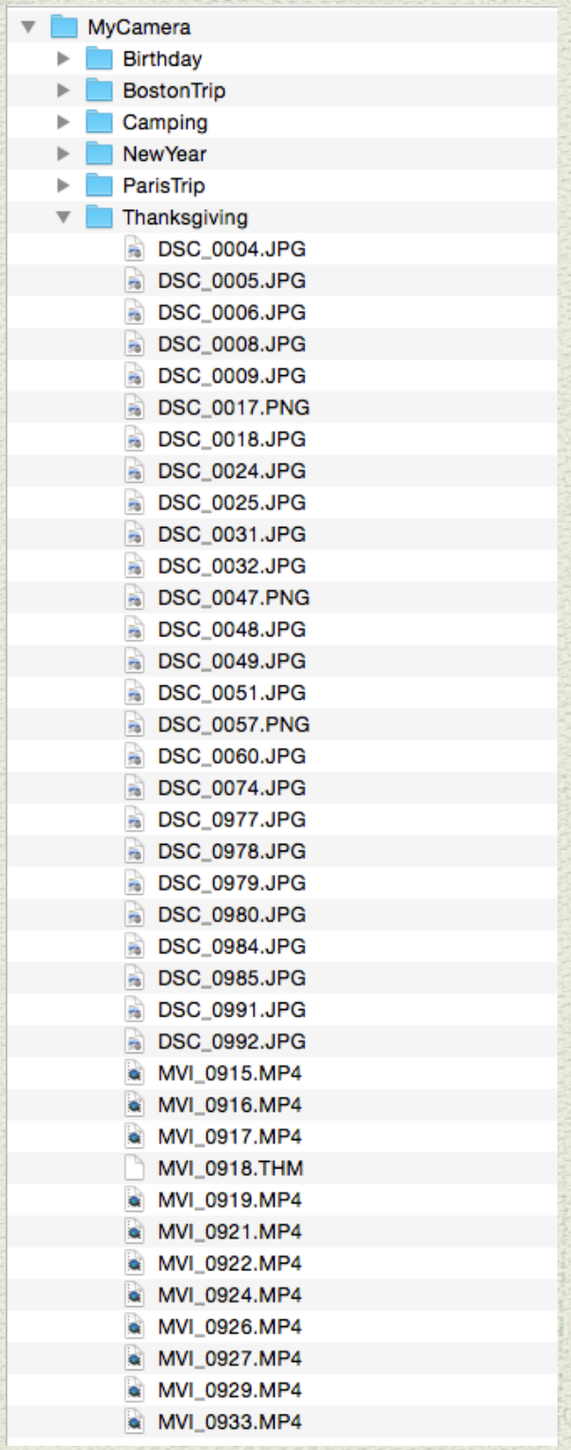
- But most users can't write scripts!
- **Solution:** Generate transformations automatically.



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- A new algorithm for automatically synthesizing tree transformations from input-output examples.

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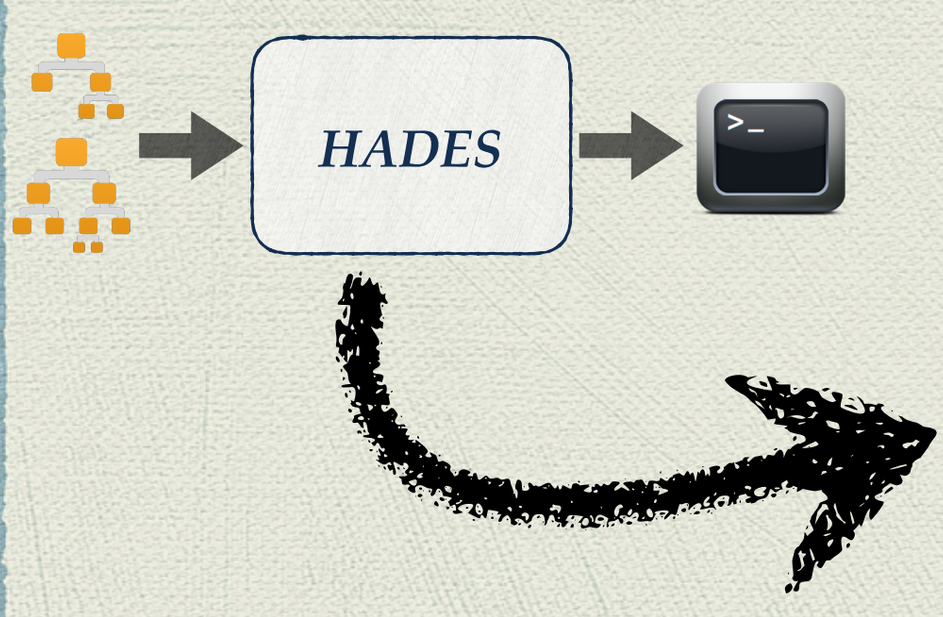
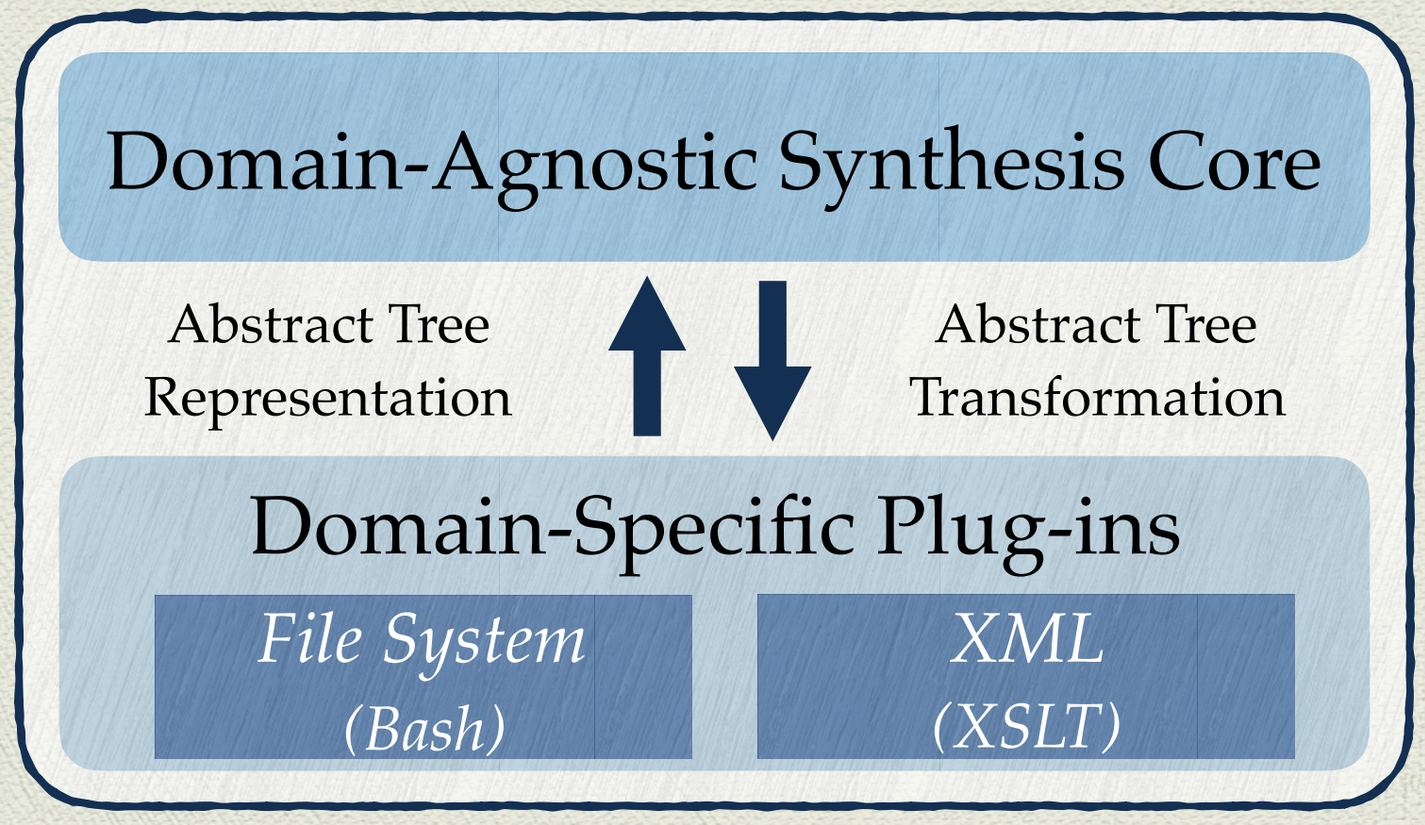
- Implementation of a domain-agnostic synthesis core and a set of domain-specific plug-ins for *File System* and *XML*.





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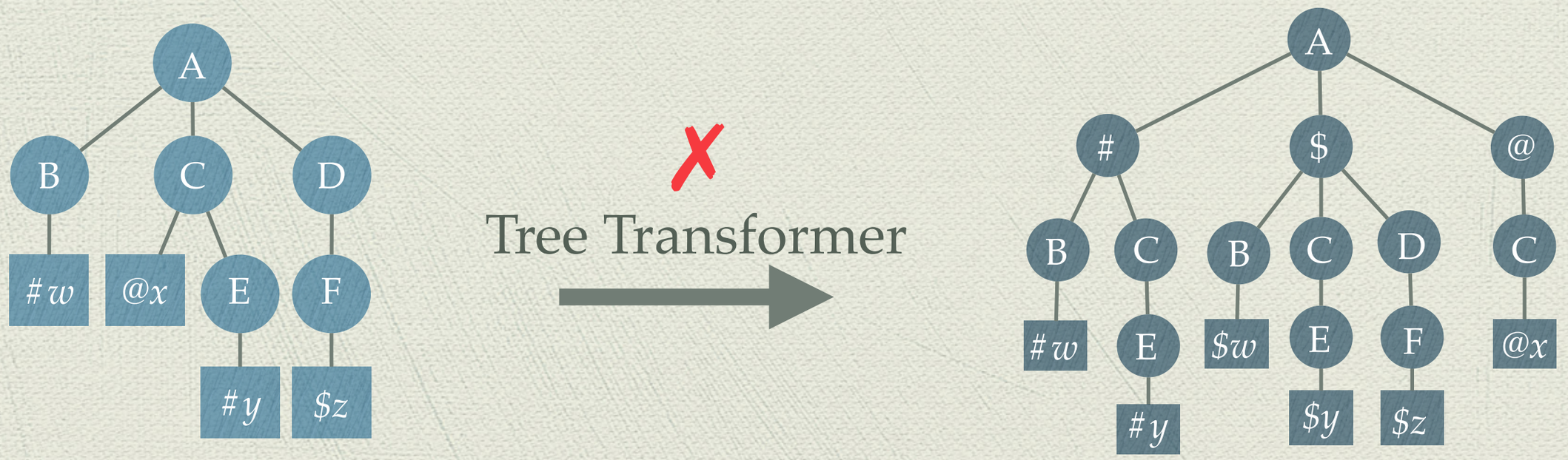
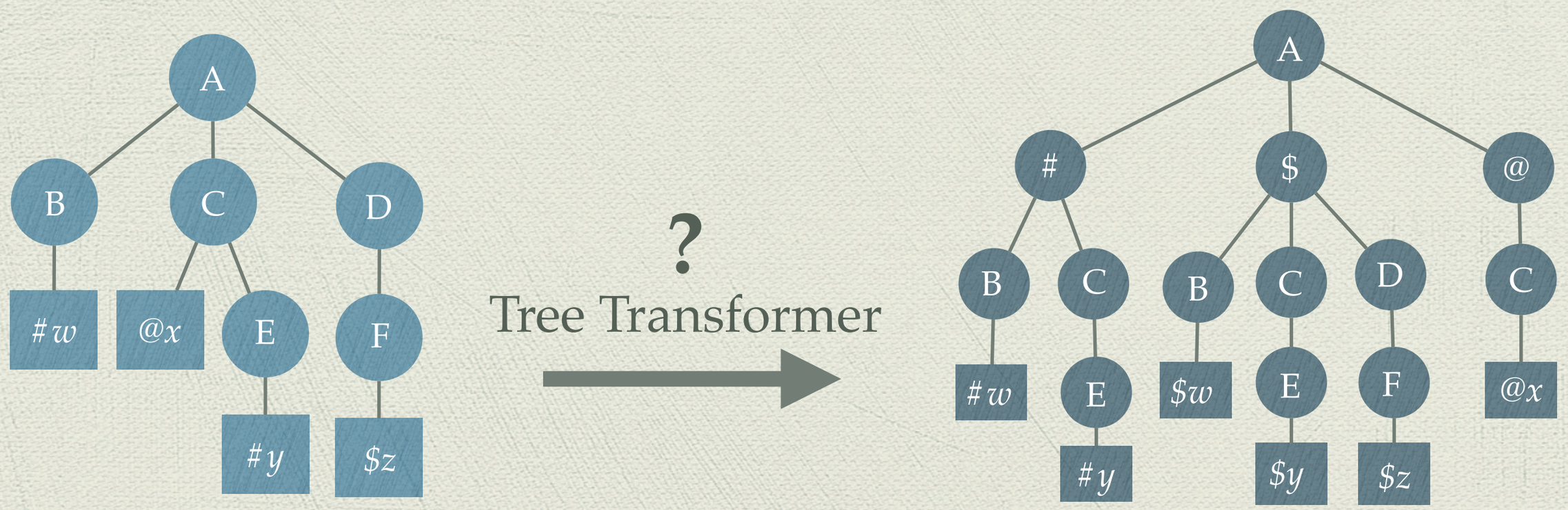
  - Synthesize higher-order functional programs

- Don't support many tree transformations (e.g. transformation which alters the tree structure)
  - Hard to implement using functional approach



Key Idea

- Different way to look at tree transformation:



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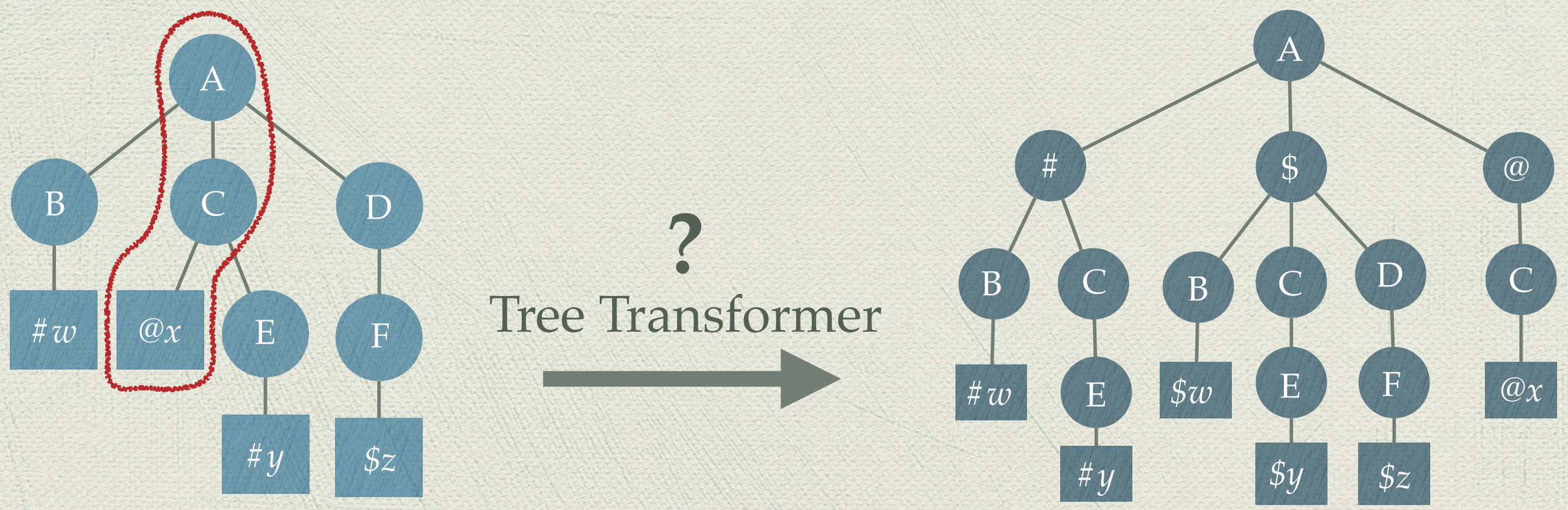

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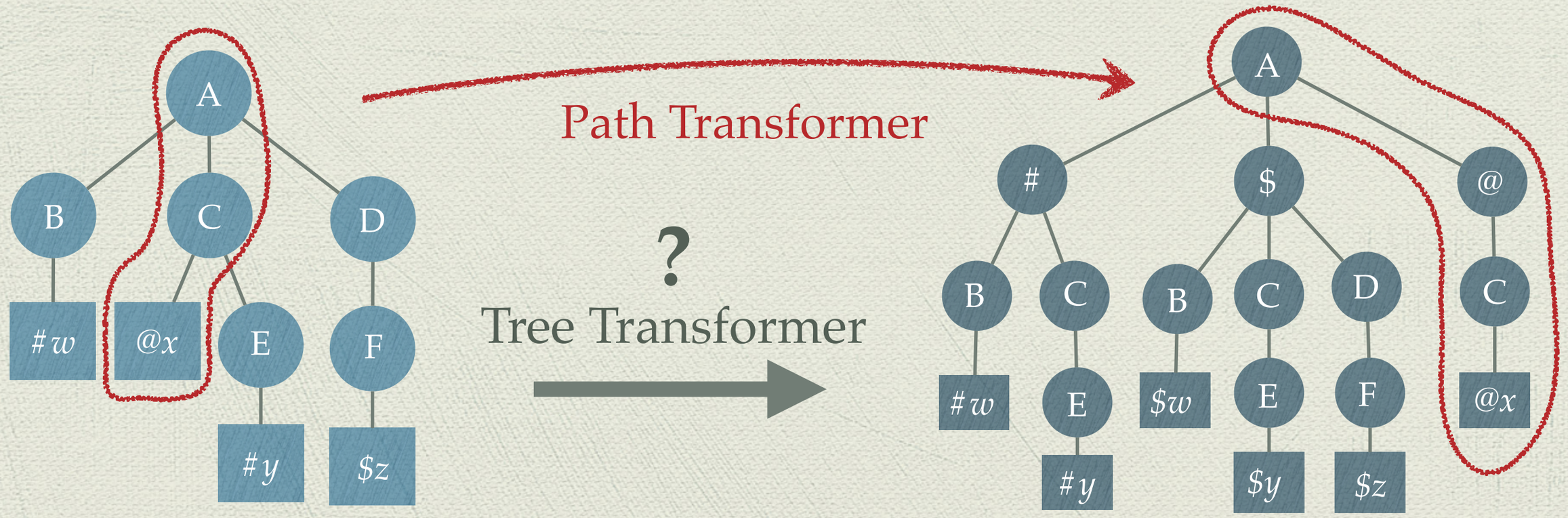

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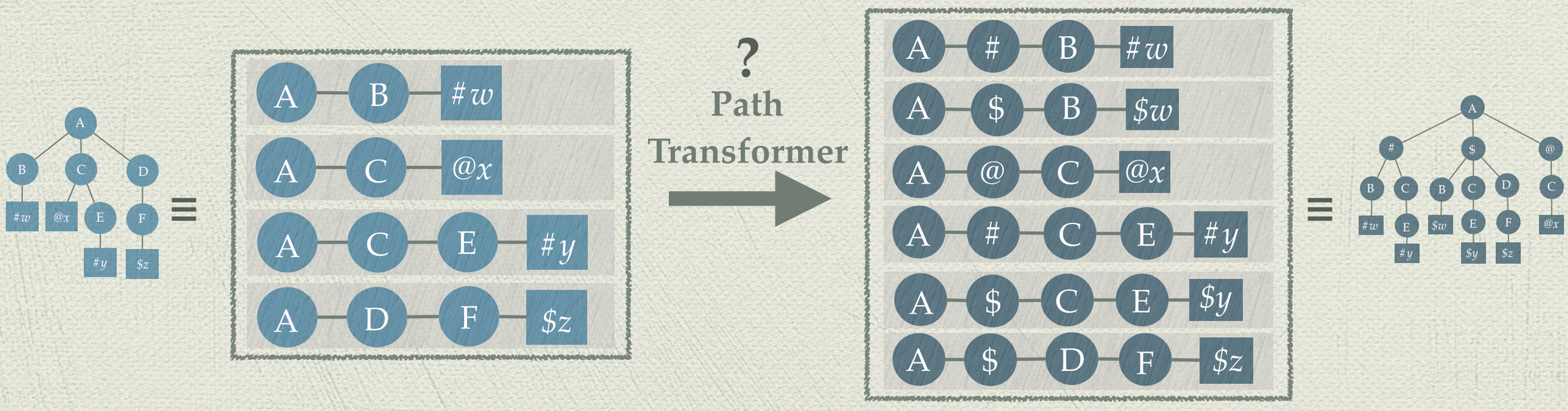
> Reduce tree transformation synthesis to synthesis of a transformer over paths of the tree.



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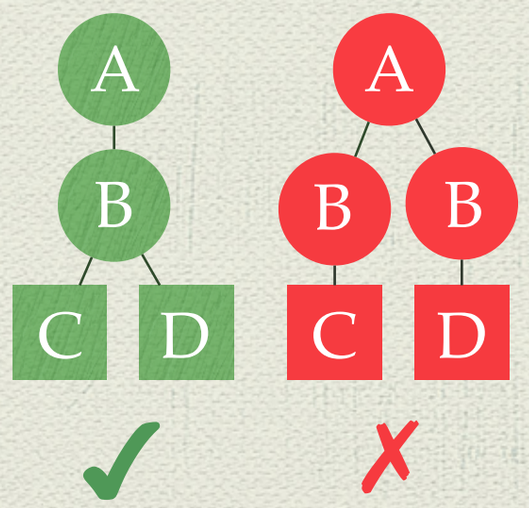
- Handles a broad class of tree transformations.
- Relies on a natural assumption:
  - Trees do not have siblings with the same label.
  - Many applications (e.g. File System) preserve this.



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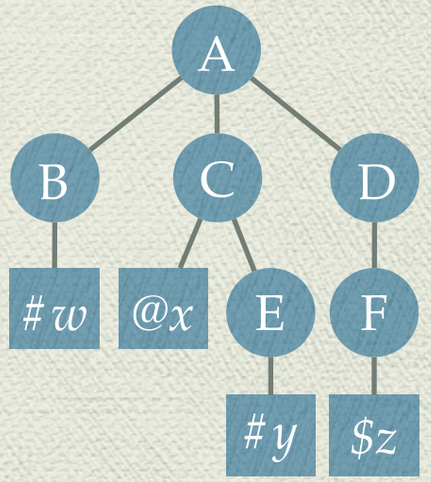

Tree Transformation

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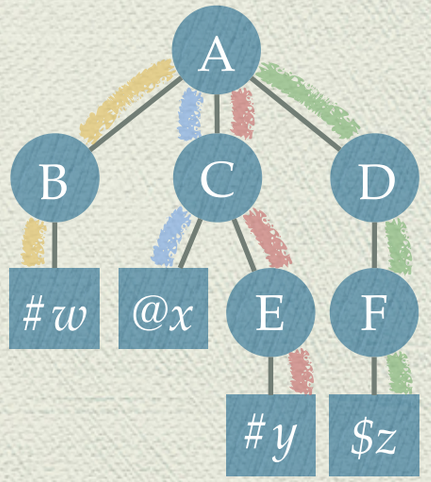
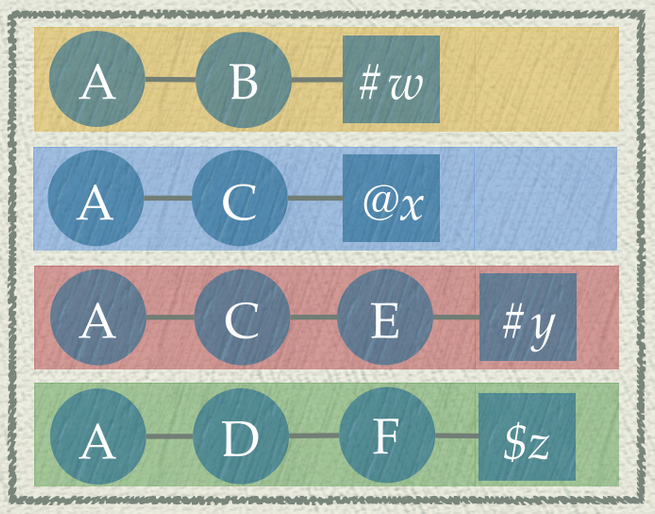


Furcation



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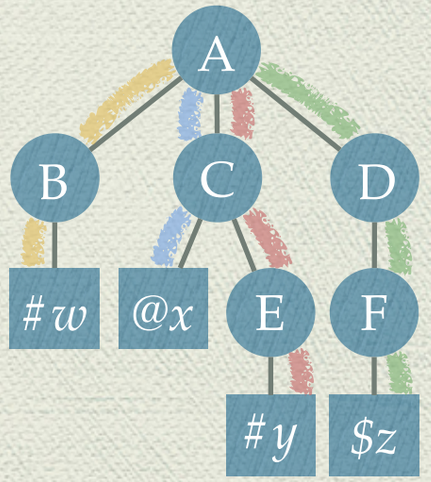

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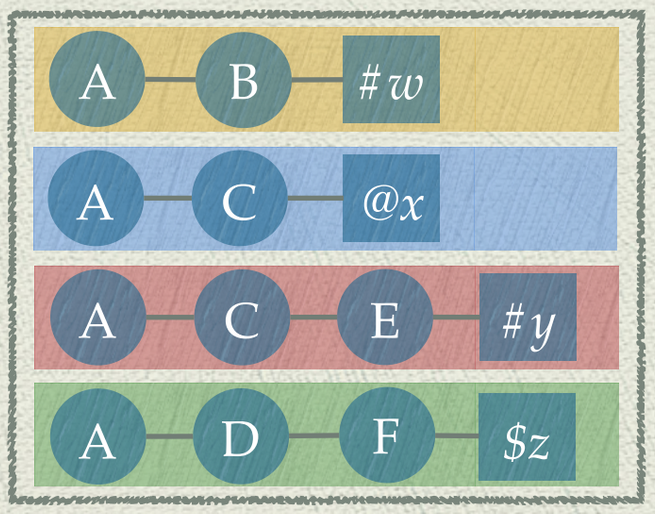

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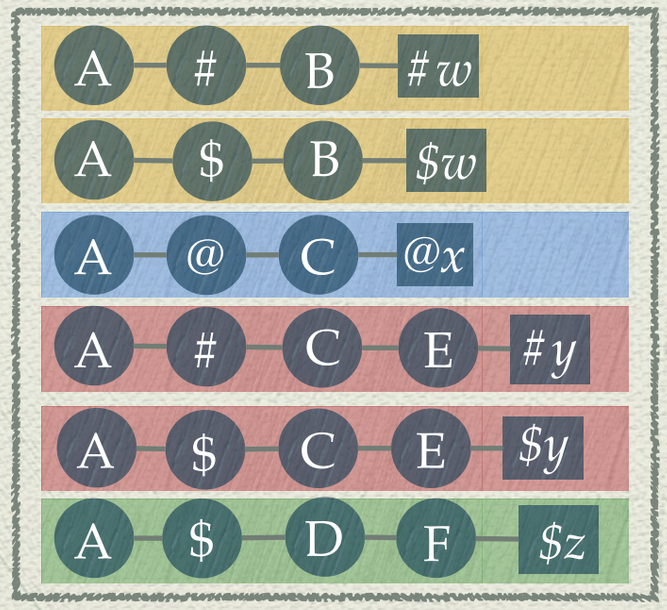

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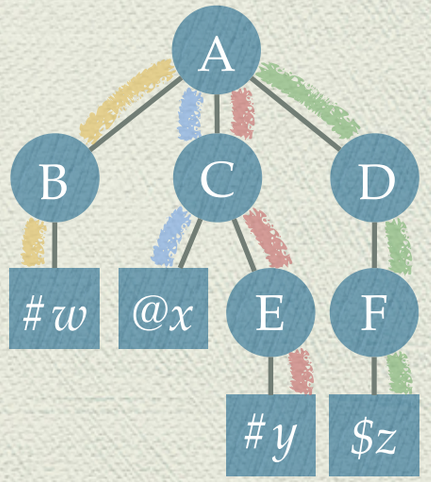

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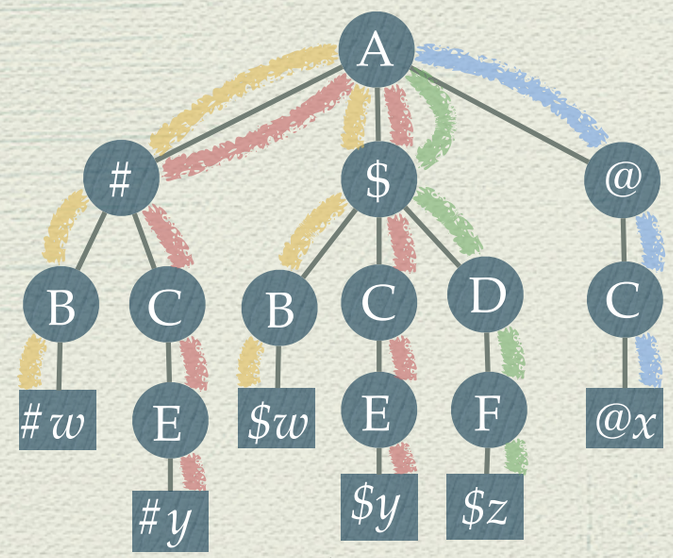
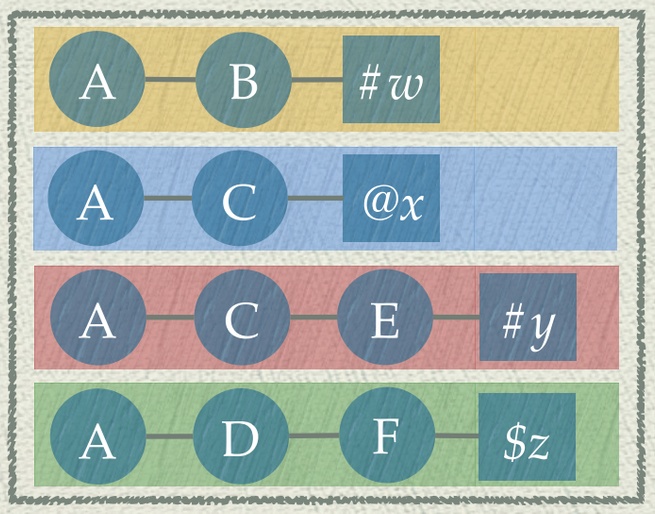


Splicing



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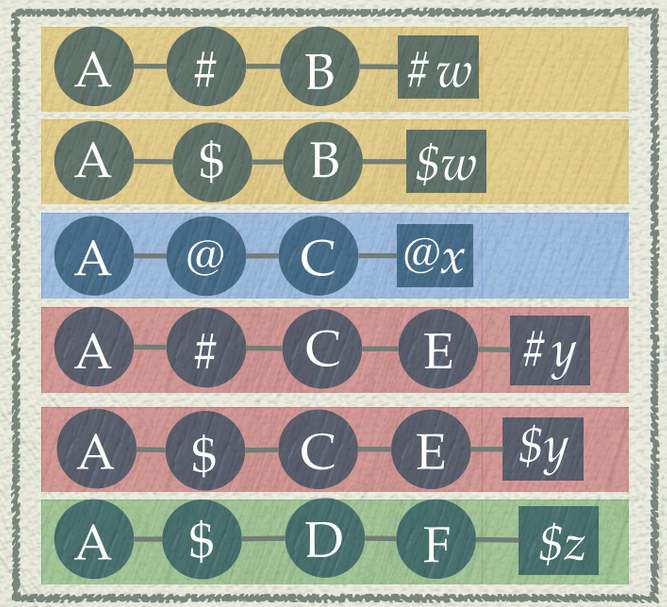

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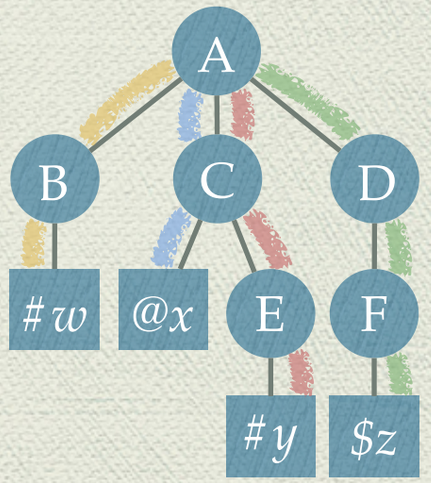

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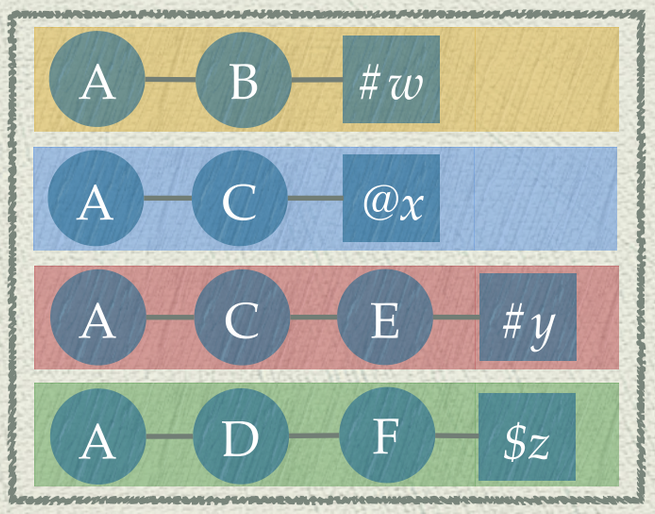

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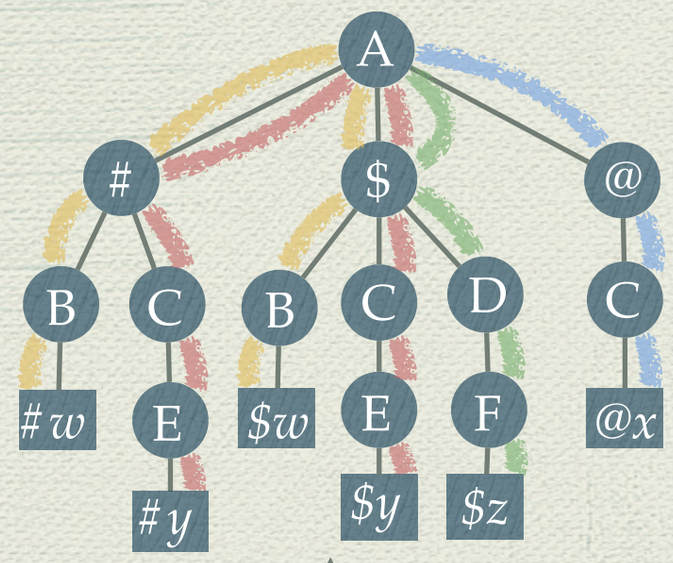

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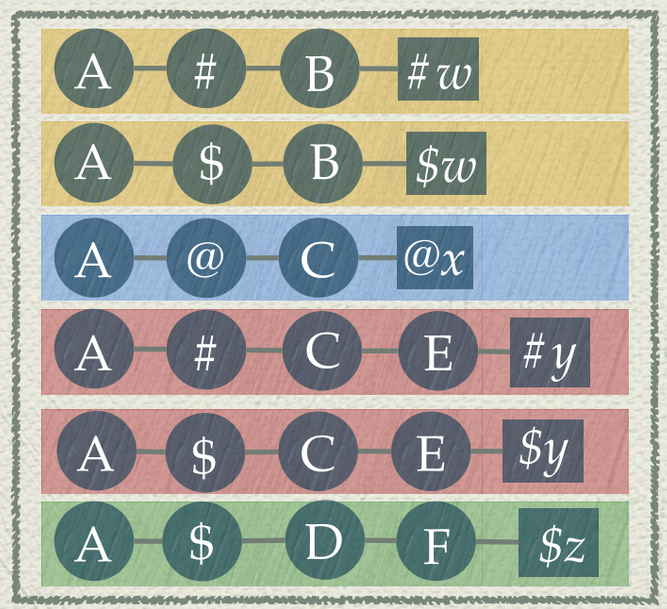

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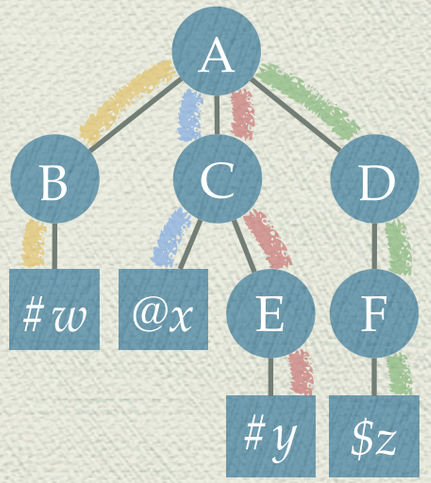

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To be synthesized

Splicing

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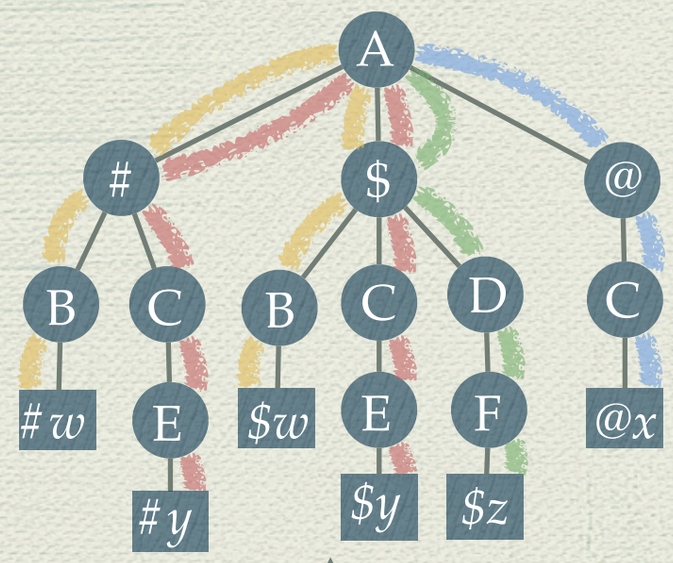
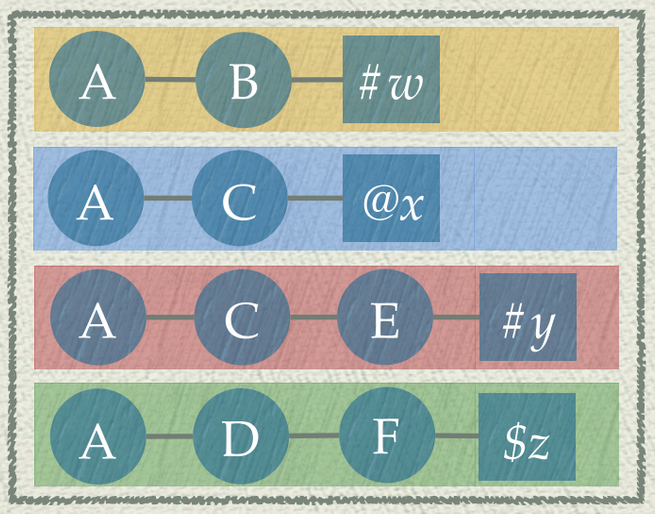
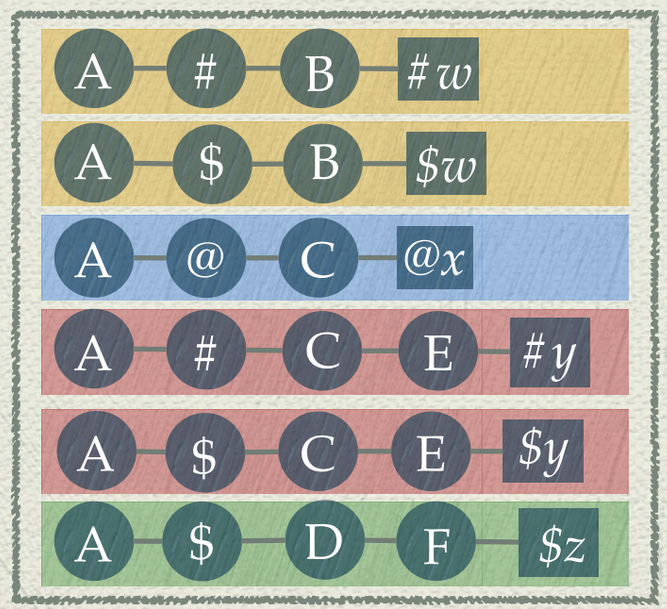
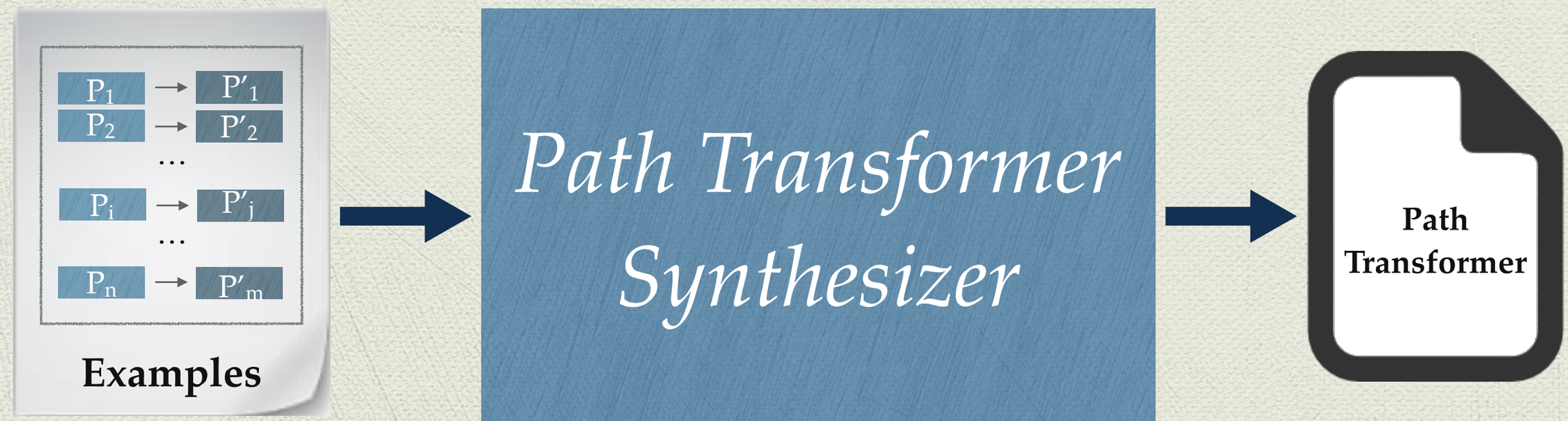






Path Transformation Synthesis

- New algorithm for path transformation synthesis based on:
  - **Enumerative search**
  - **SMT solving**
  - **Decision tree learning**



Path Transformer Language

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  if ($C_i(p)$) then $U_i(p)$

PathTransformer (p)

$\{C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p}) \; ; \ldots ; \; C_n(\mathrm{p}) \rightarrow U_n(\mathrm{p})\}$

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- Predicate C_i:
  Check properties on input path
- Unifier U_i:
  Conditional free transformer function

PathTransformer (p)

$\{C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p}) \; ; \ldots ; \; C_n(\mathrm{p}) \rightarrow U_n(\mathrm{p})\}$

Path Transformer Language

Need simple language that achieves good tradeoff between expressiveness and ease of synthesis

- Set of conditional statements:
  if ($C_i(p)$) then $U_i(p)$
- Predicate C_i:
  Check properties on input path
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PathTransformer (p)

$$\{C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p}) \; ; \ldots ; \; C_n(\mathrm{p}) \rightarrow U_n(\mathrm{p})\}$$

$$U_i(\mathrm{p}) = \mathrm{concat}\,(g_1(\mathrm{p}), \ldots, g_m(\mathrm{p}))$$

$$g_j(\mathrm{p}) = \mathrm{map}\; F_j\; \mathrm{subpath}(\mathrm{p}, t_j, t'_j)$$

Drawn from a finite vocabulary (e.g. doc2pdf, chmod, zip, …)

start index

end index

Partition

$$\{C_1(\mathbf{p}) \rightarrow U_1(\mathbf{p}) \; ; \ldots ; \; C_n(\mathbf{p}) \rightarrow U_n(\mathbf{p})\}$$

$$U_i(\mathrm{p}) = \mathrm{concat}\,(g_1(\mathrm{p}), \ldots, g_m(\mathrm{p}))$$

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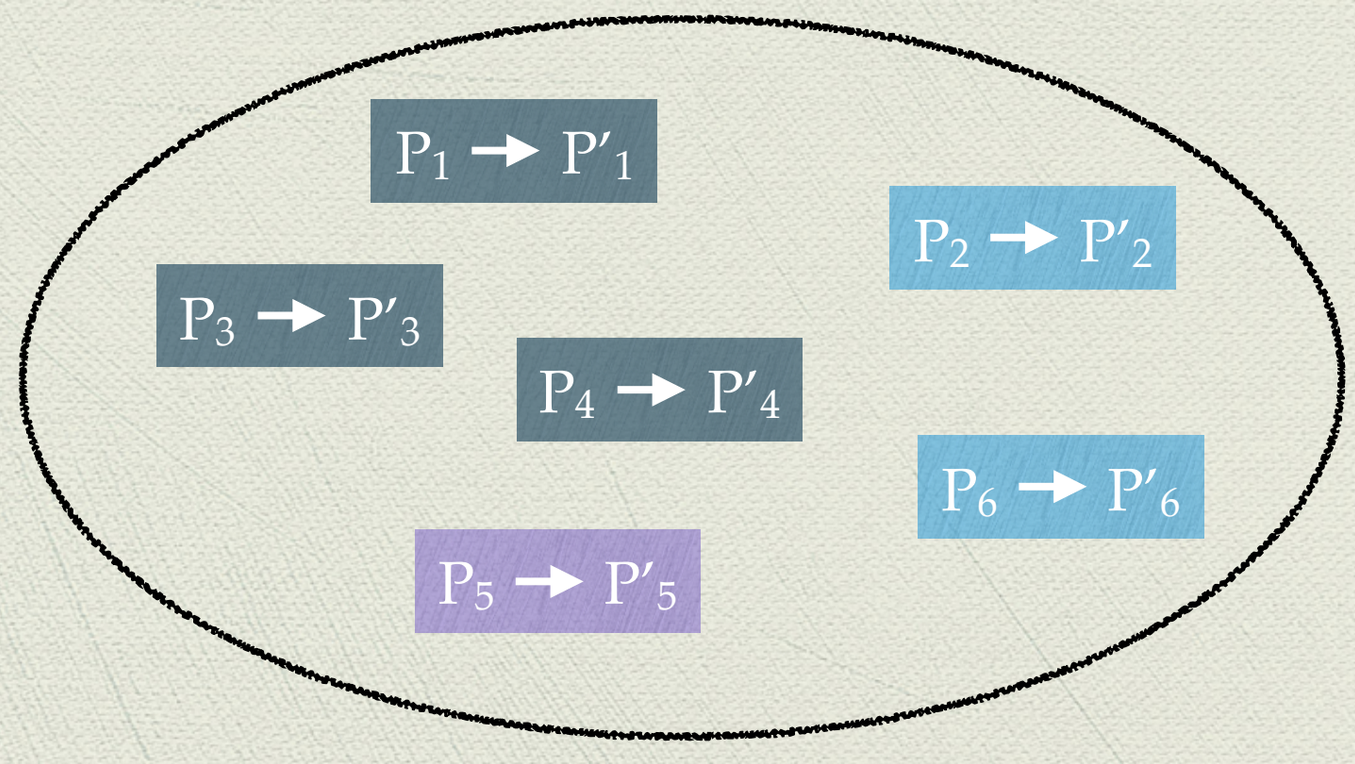

Partition

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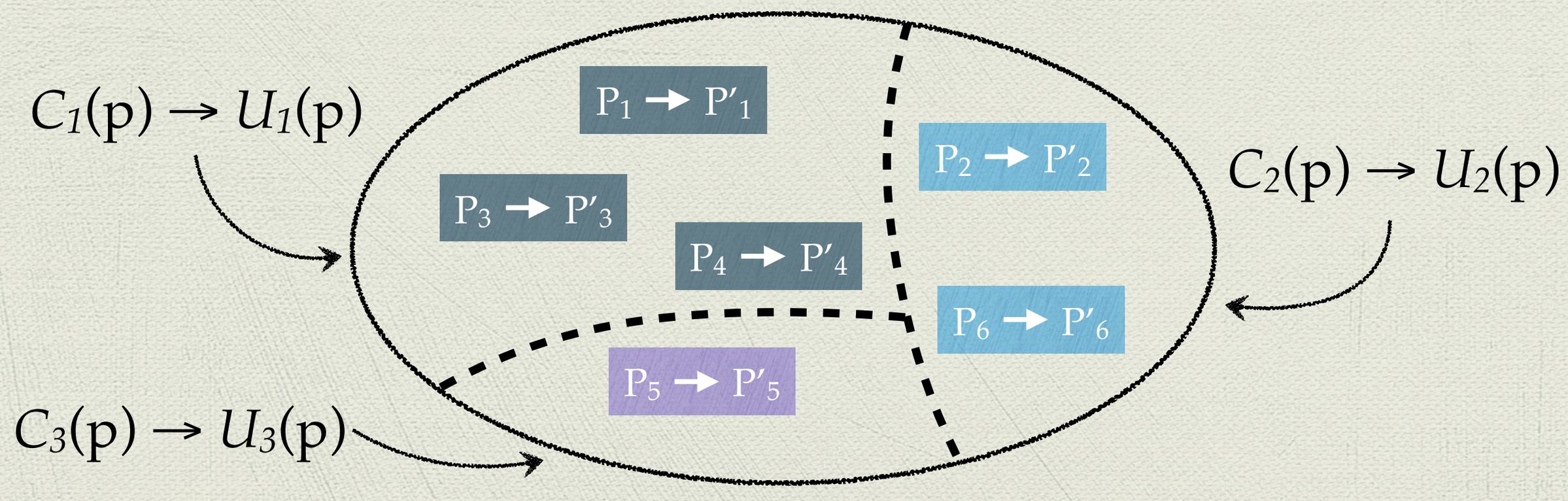

Partition

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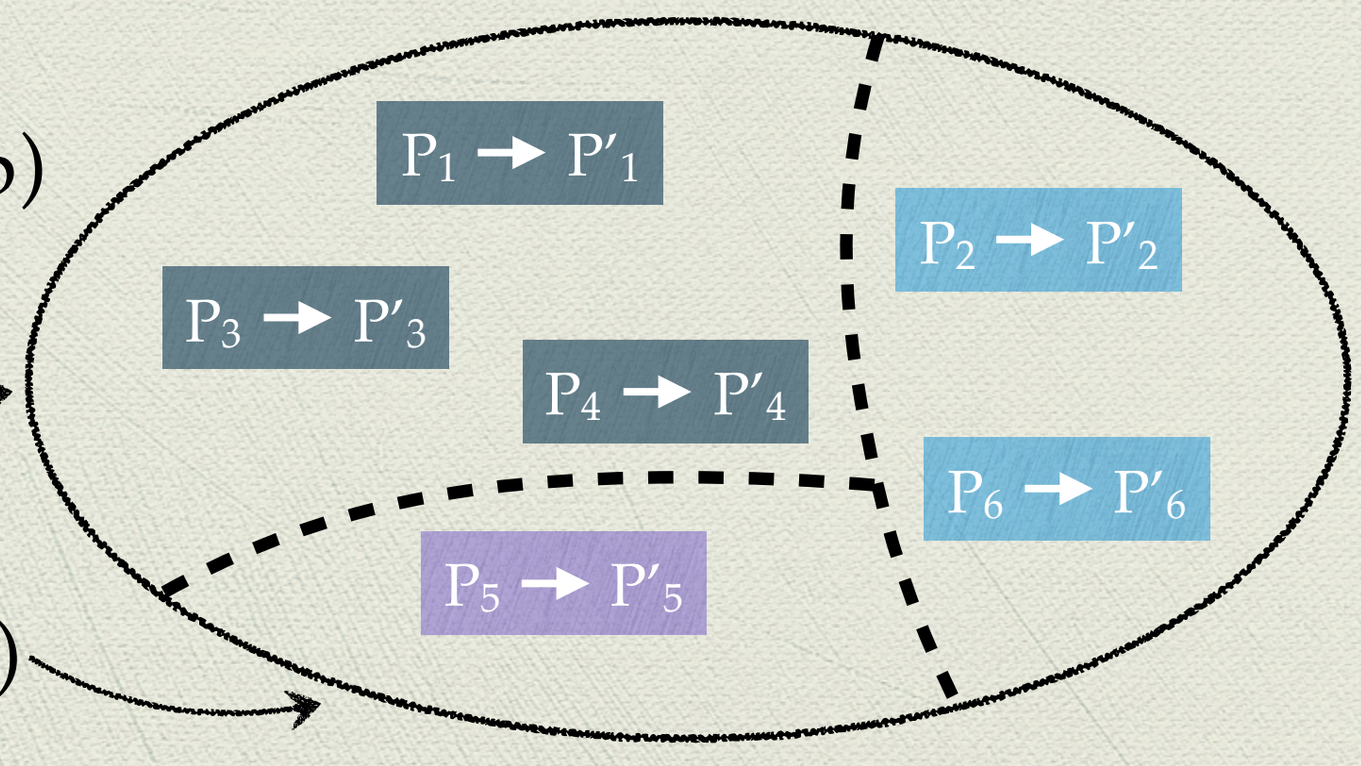
Partition 1
$C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p})$

Partition 2
$C_2(\mathrm{p}) \rightarrow U_2(\mathrm{p})$

Partition 3
$C_3(\mathrm{p}) \rightarrow U_3(\mathrm{p})$



Unifier

$$\{C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p}) \; ; \ldots ; \; C_n(\mathrm{p}) \rightarrow U_n(\mathrm{p})\}$$

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Input Path

Unifier

$$\{C_1(\mathrm{p}) \rightarrow U_1(\mathrm{p}) \; ; \ldots ; \; C_n(\mathrm{p}) \rightarrow U_n(\mathrm{p})\}$$

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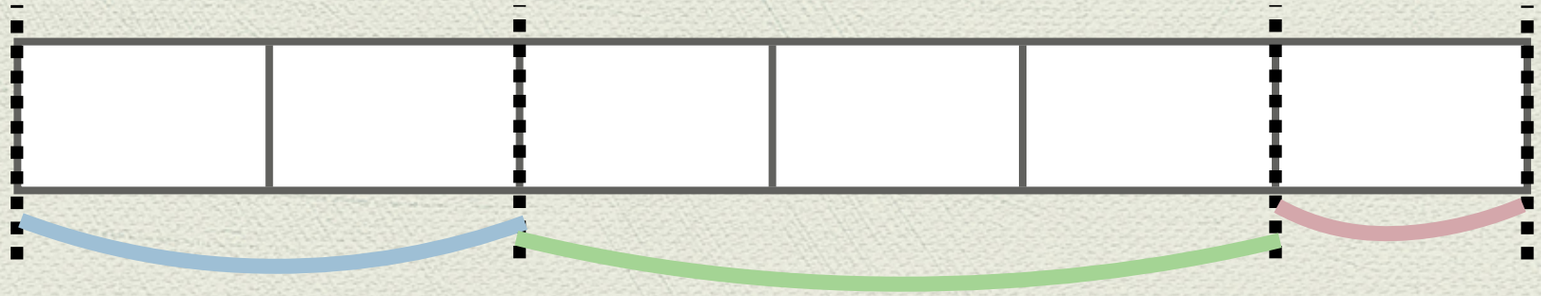
Input Path



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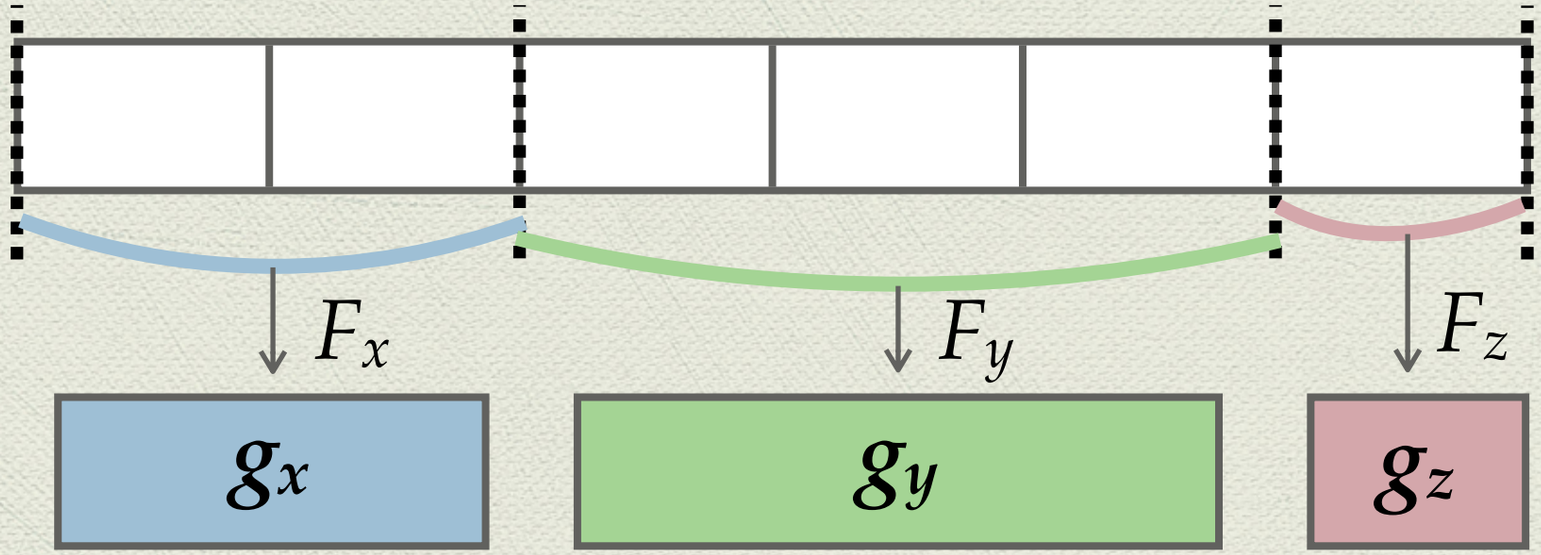
Input Path

Path Segments



Unifier

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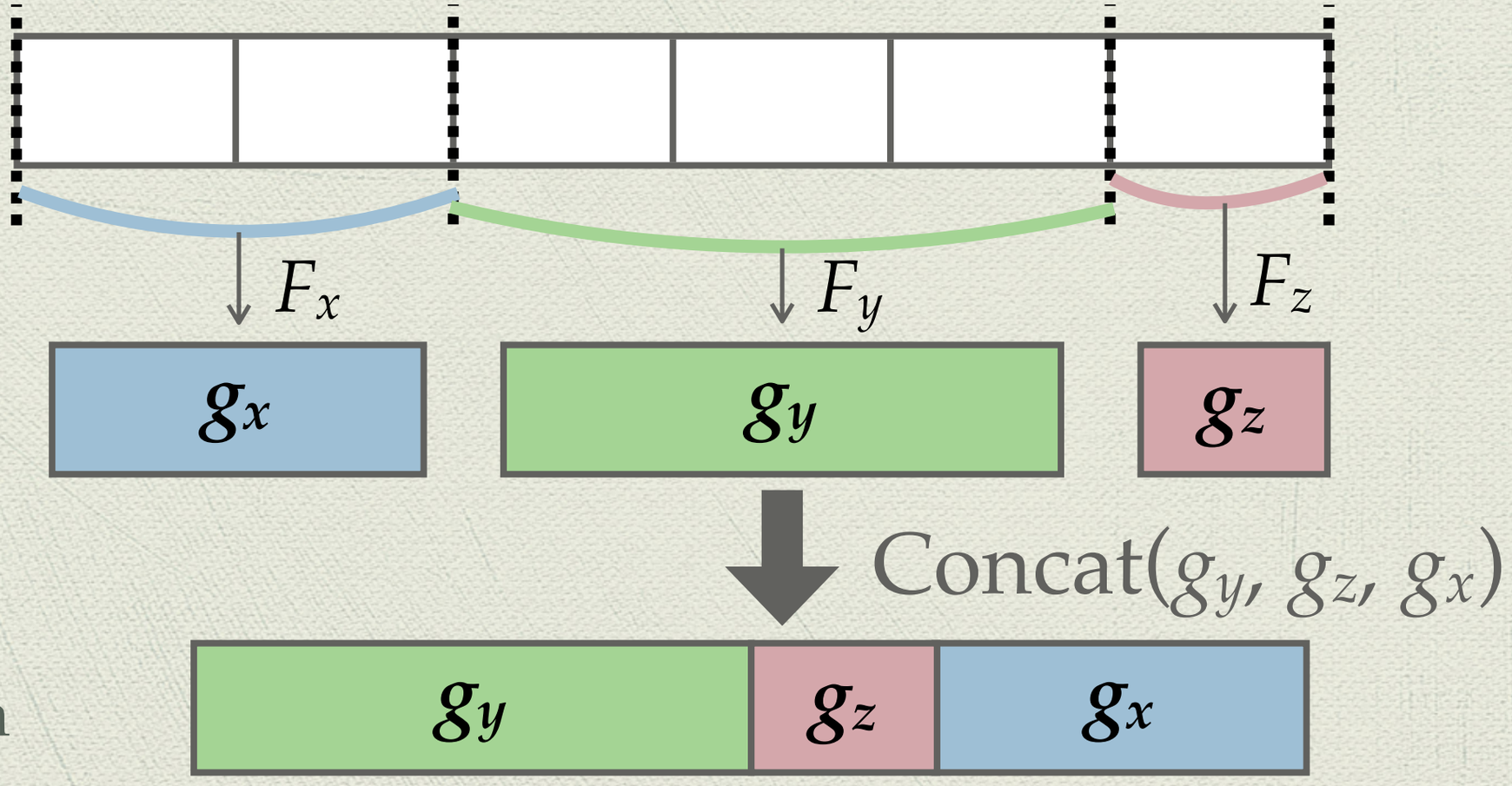


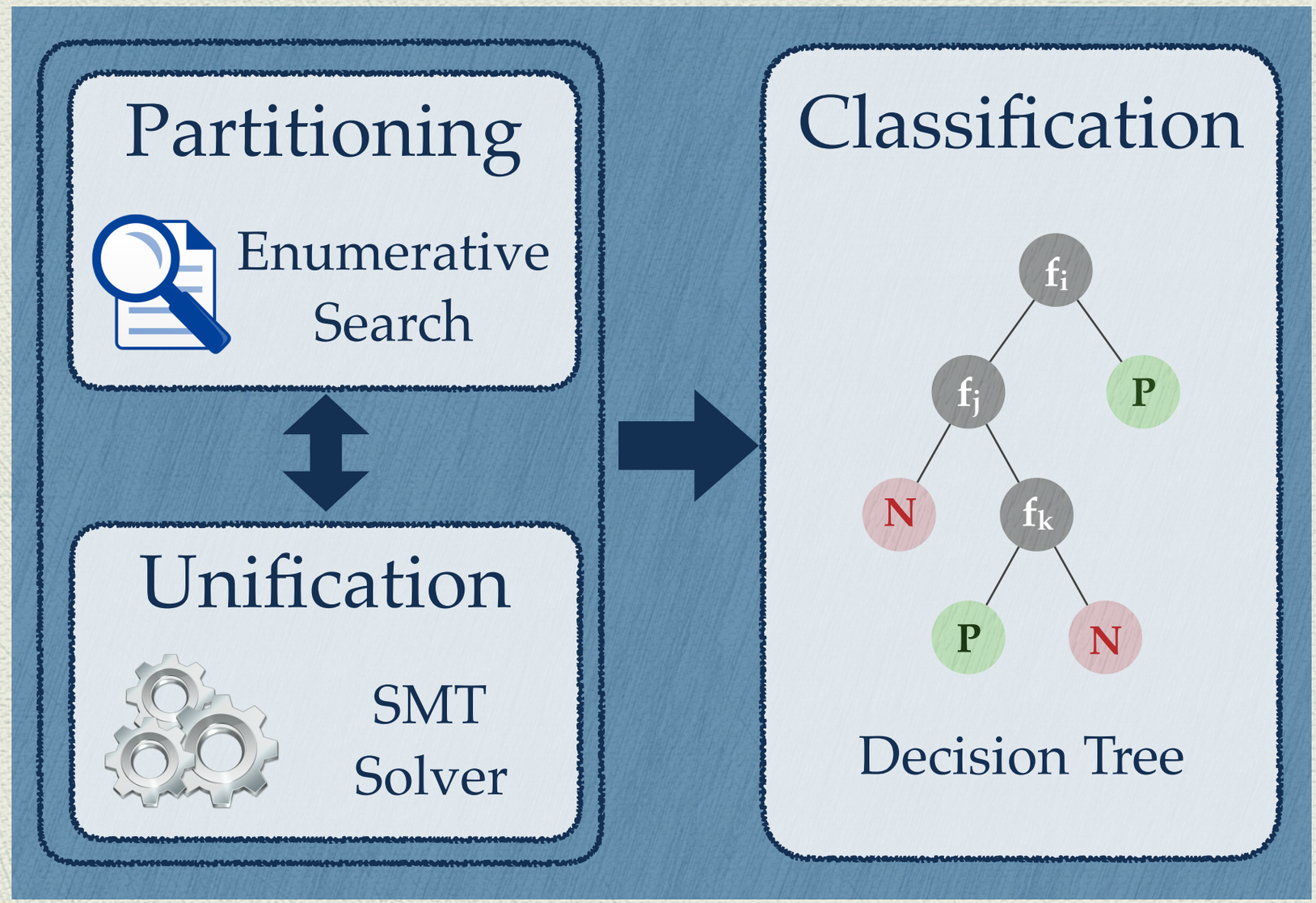
Goal of Synthesis

- Generalization: Find the simplest path transformer.
  - Simplest ≡ minimum number of conditionals

Goal of Synthesis

- Generalization: Find the simplest path transformer.
  - Simplest ≡ minimum number of conditionals
- Prevents synthesis of a transformer overfitted to examples.

Path Transformer Synthesizer

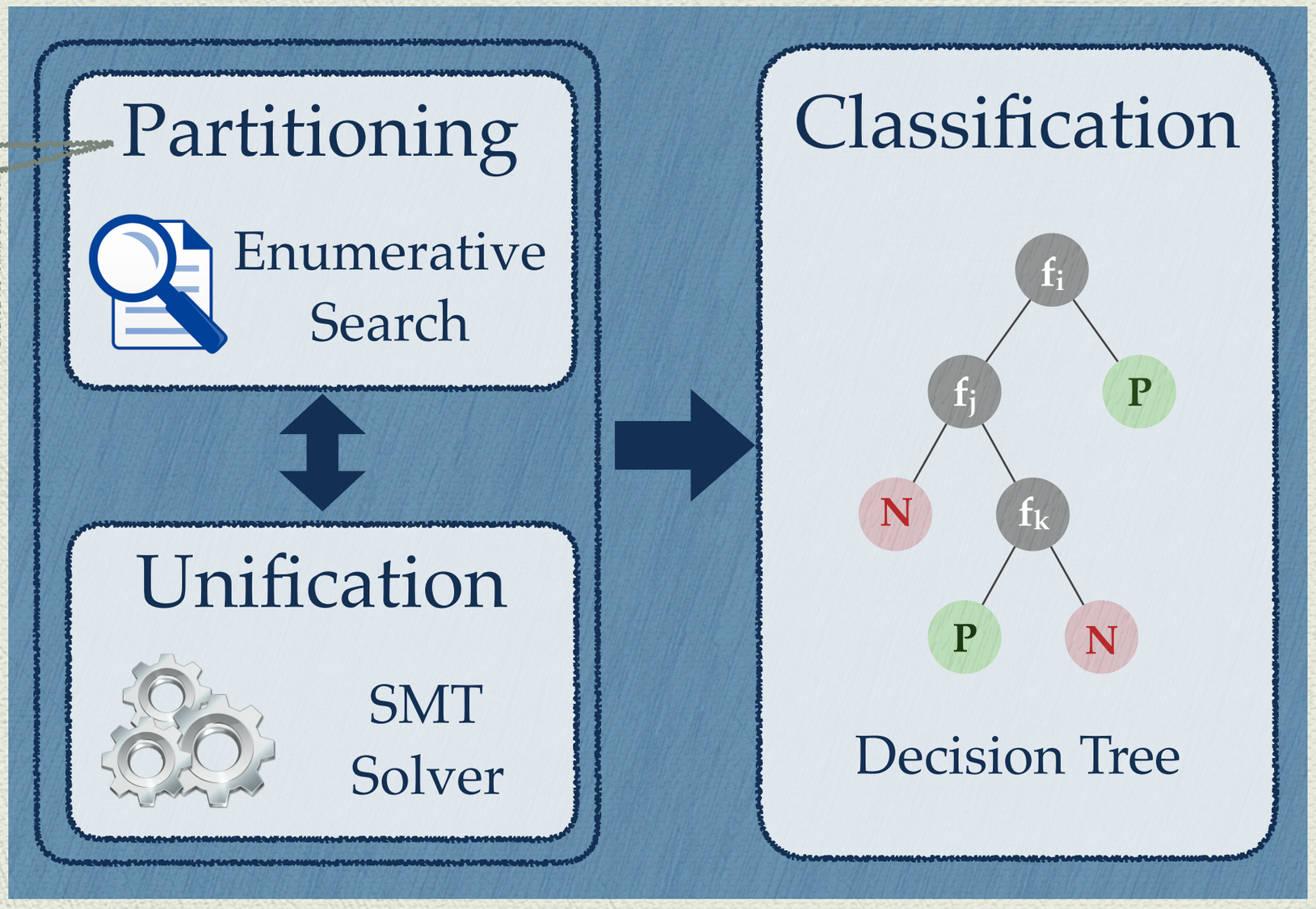


Path Transformer Language

$$\{C_1 \rightarrow U_1 ; \ldots ; C_i \rightarrow U_i ; \ldots ; C_n \rightarrow U_n \}$$

Path Transformer Synthesizer

Find the number of conditionals



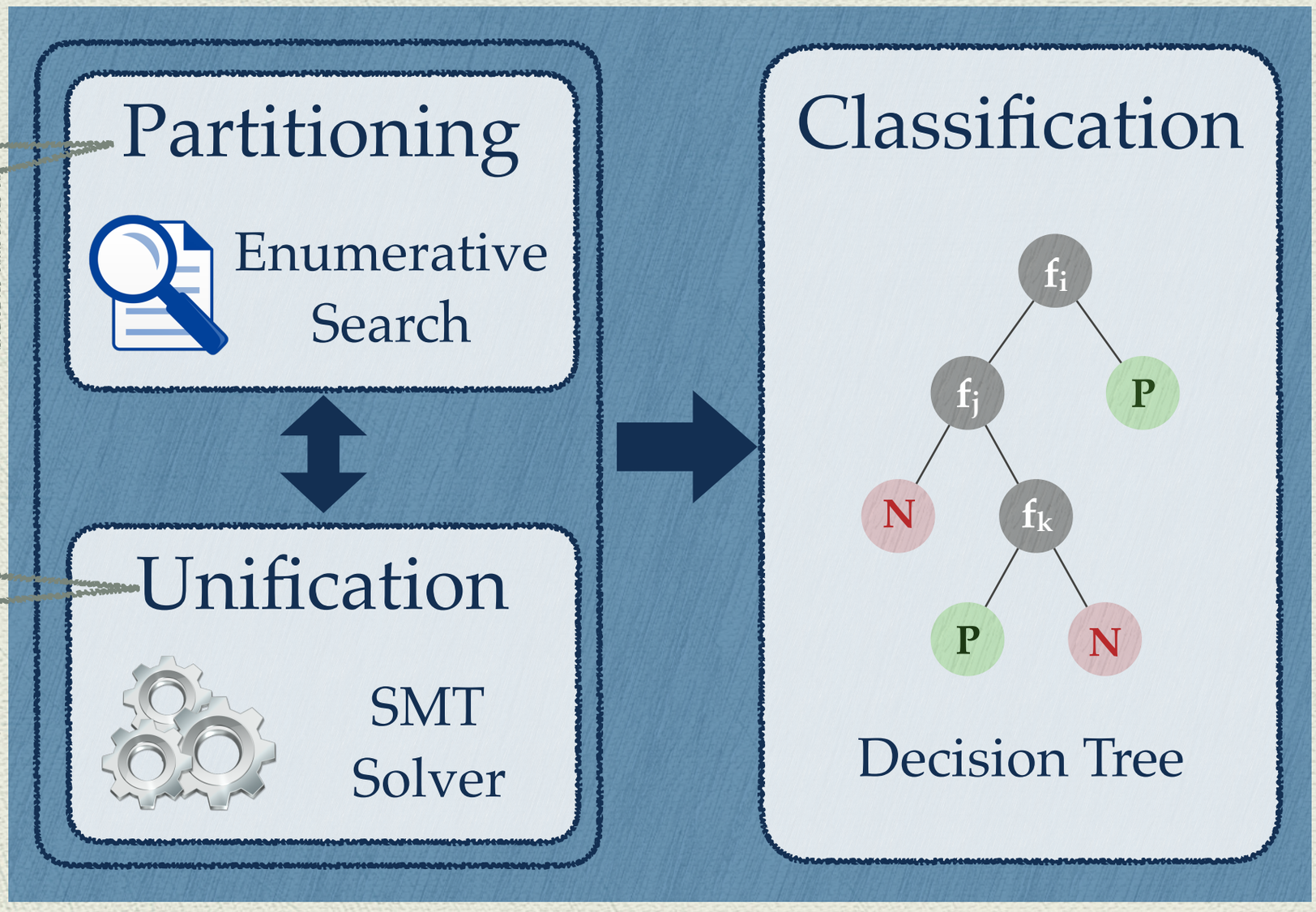
Path Transformer Language

$$\{C_1 \rightarrow U_1 ; \ldots ; C_i \rightarrow U_i ; \ldots ; C_n \rightarrow U_n \}$$

Path Transformer Synthesizer

Find the number of conditionals

Find unifier U_i for each partition



Path Transformer Language

$$\{C_1 \rightarrow U_1 ; \ldots ; C_i \rightarrow U_i ; \ldots ; C_n \rightarrow U_n \}$$

Path Transformer Synthesizer

Find the number of conditionals

Partitioning

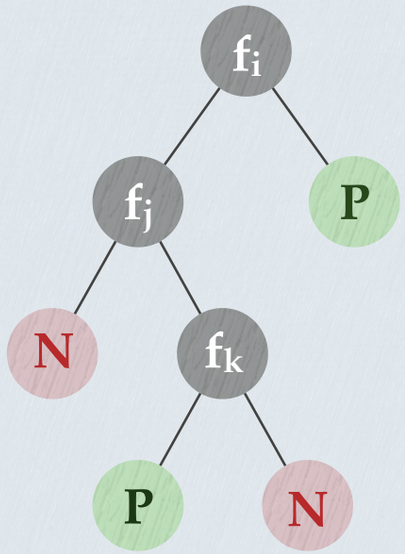
Enumerative Search

Unification

SMT Solver

Find unifier U_i for each partition

Classification



Decision Tree

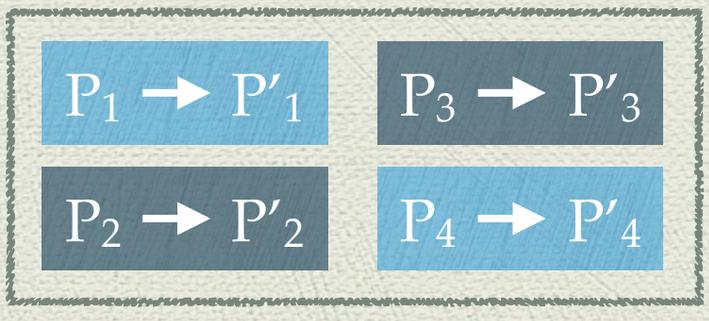
Find predicate C_i for each partition

Path Transformer Language

$$\{C_1 \rightarrow U_1 ; \ldots ; C_i \rightarrow U_i ; \ldots ; C_n \rightarrow U_n \}$$

Partitioning

Divide examples to minimum number of unifiable subsets



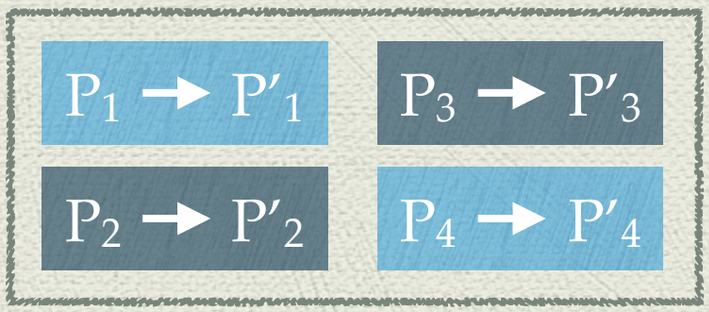
G $P'_1 = G(P_1)$ $P'_4 = G(P_4)$

F $P'_2 = F(P_2)$ $P'_3 = F(P_3)$

Partitioning

Divide examples to minimum number of unifiable subsets

- Conduct **enumerative search:**
  - Increase number of subsets until a solution is found.



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Partitioning

Divide examples to <u>minimum</u> number of unifiable subsets

- Conduct **enumerative search:**
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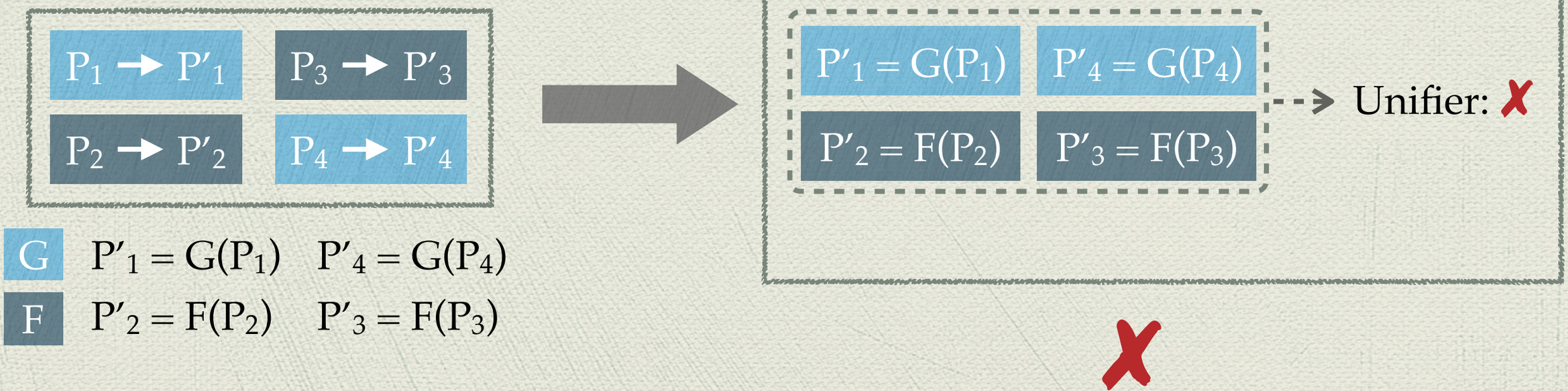
number of subsets = **1**



Partitioning

Divide examples to <u>minimum</u> number of unifiable subsets

- Conduct **enumerative search:**
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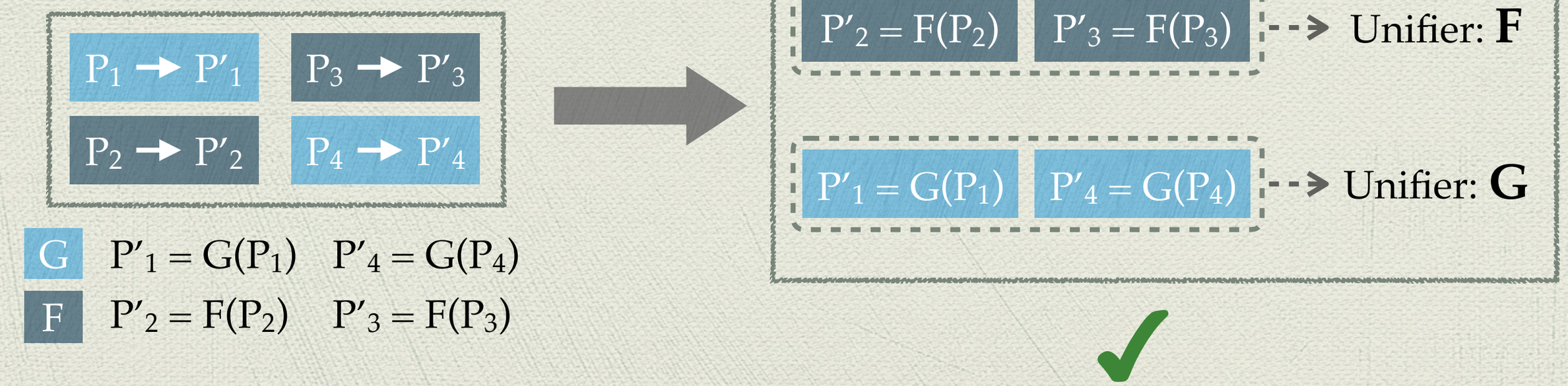
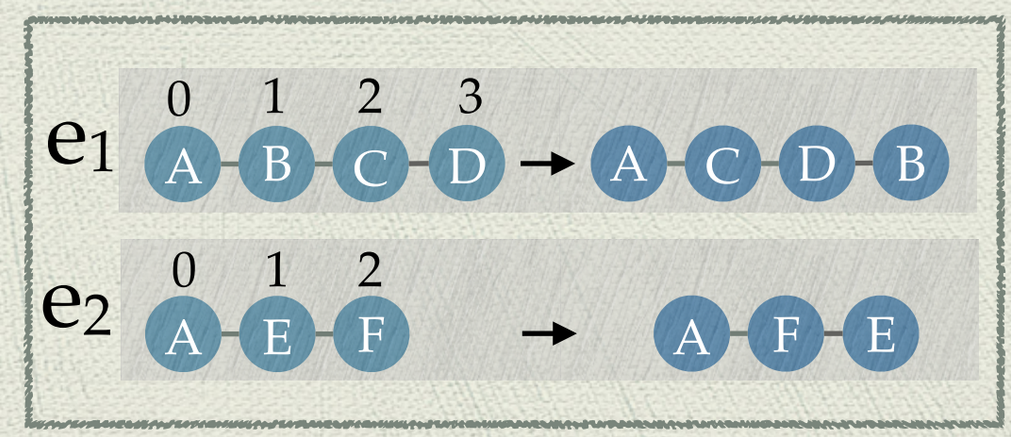


Unification

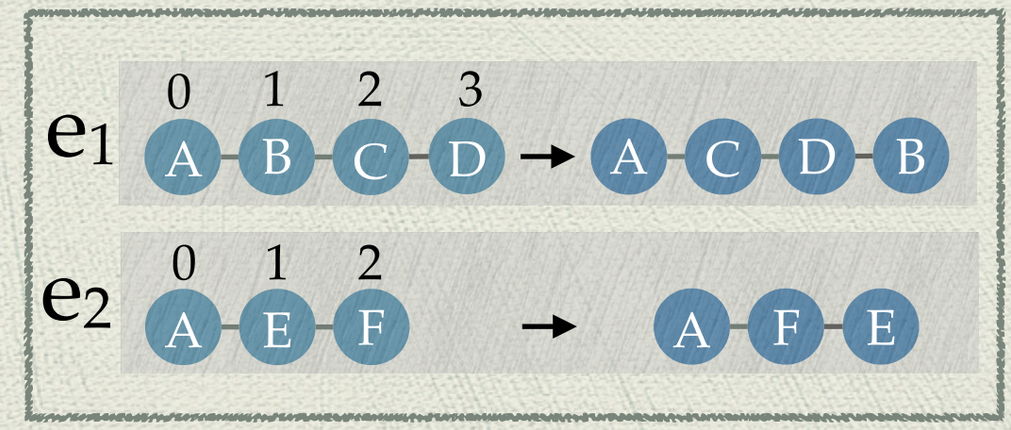
Determine if a subset of examples has a *unifier* or not



Unification

Determine if a subset of examples has a *unifier* or not

- Represent examples using numerical representation.
  - Output path represented as a permutation of input path.



e_1.out = [0, 2, 3, 1]

e_2.out = [0, 2, 1]

Unification

Determine if a subset of examples has a *unifier* or not

- Represent examples using numerical representation.
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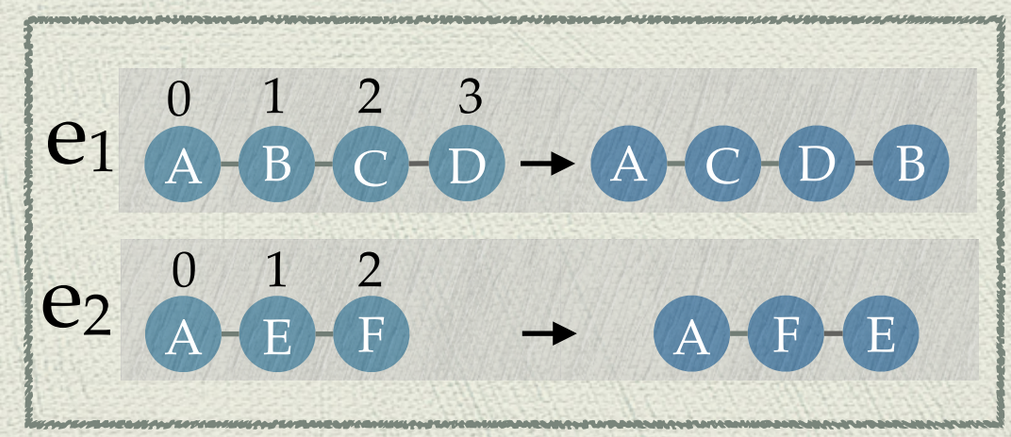
- Use **SMT solver**:
  - Check if there exists a unifier for all examples.



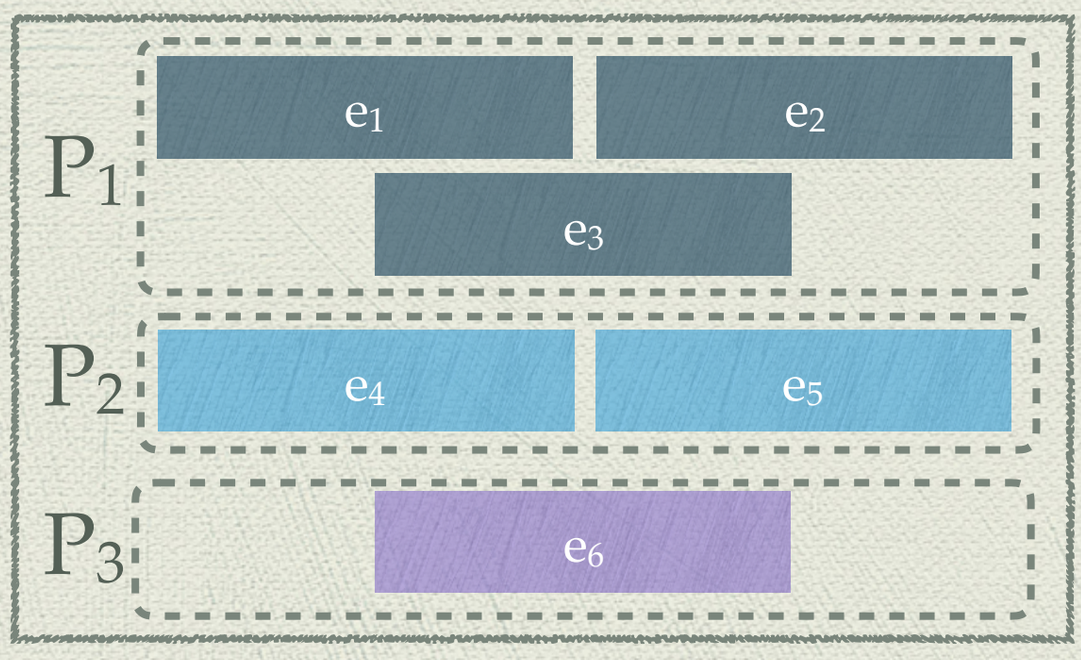
$e_1.out = [0, 2, 3, 1]$

$e_2.out = [0, 2, 1]$

Unifiable ✓

Classification

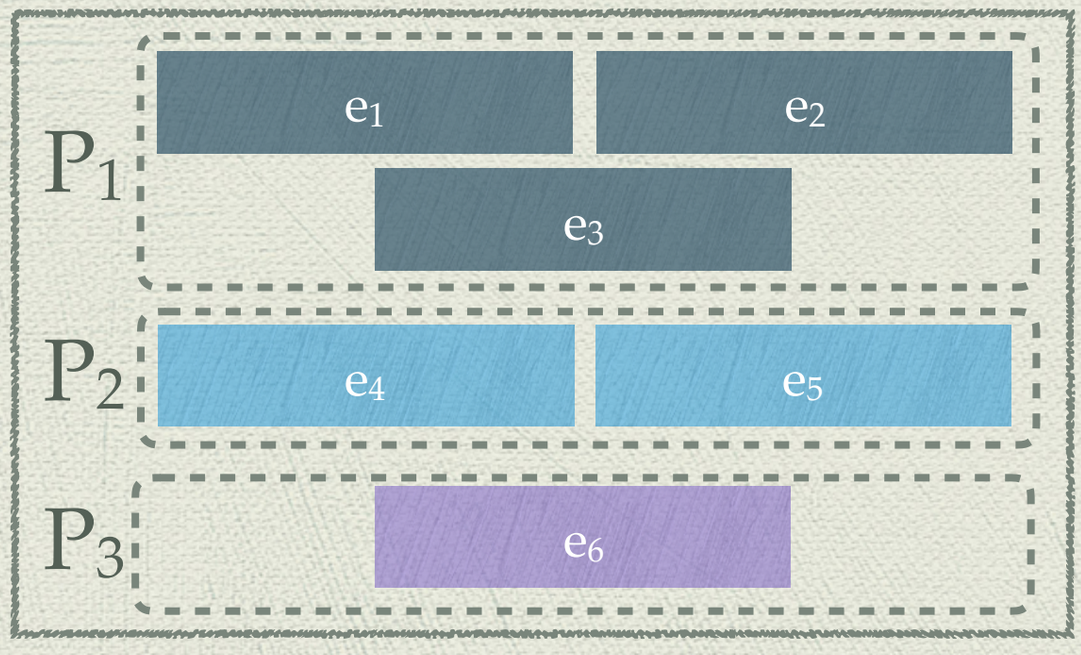
For each partition, find a predicate that differentiates examples in that partition from the rest.



Classification

For each partition, find a predicate that differentiates examples in that partition from the rest.

- Use **decision tree learning**: [ID3 algorithm, J. R. Quinlan]
  - Represent each example as a set of features.



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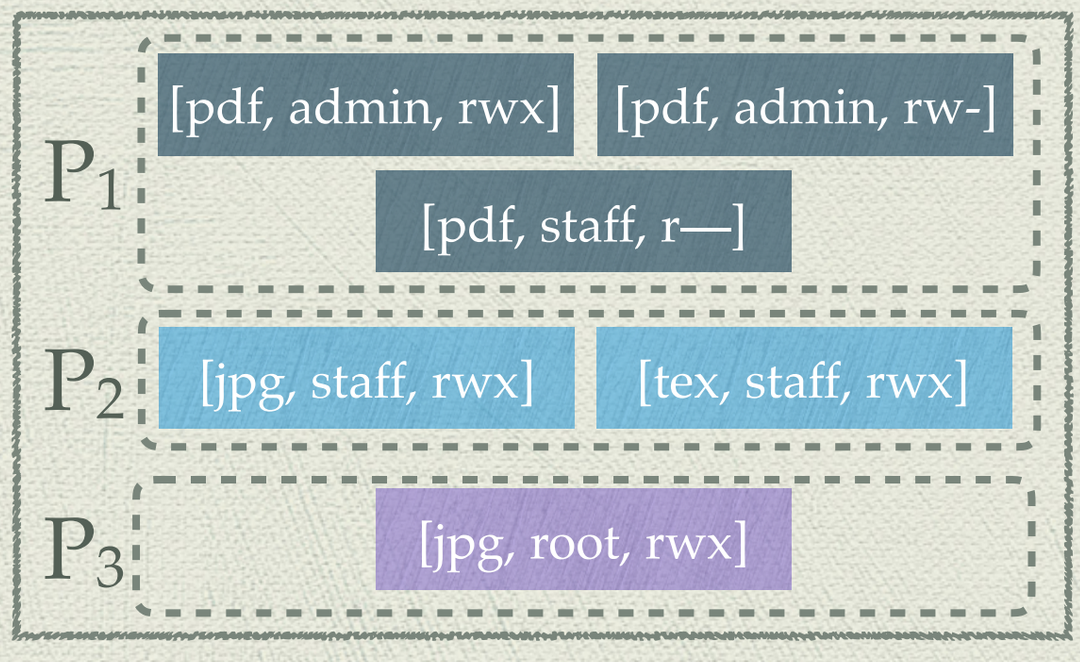

Feature set: [extension, user, permissions]

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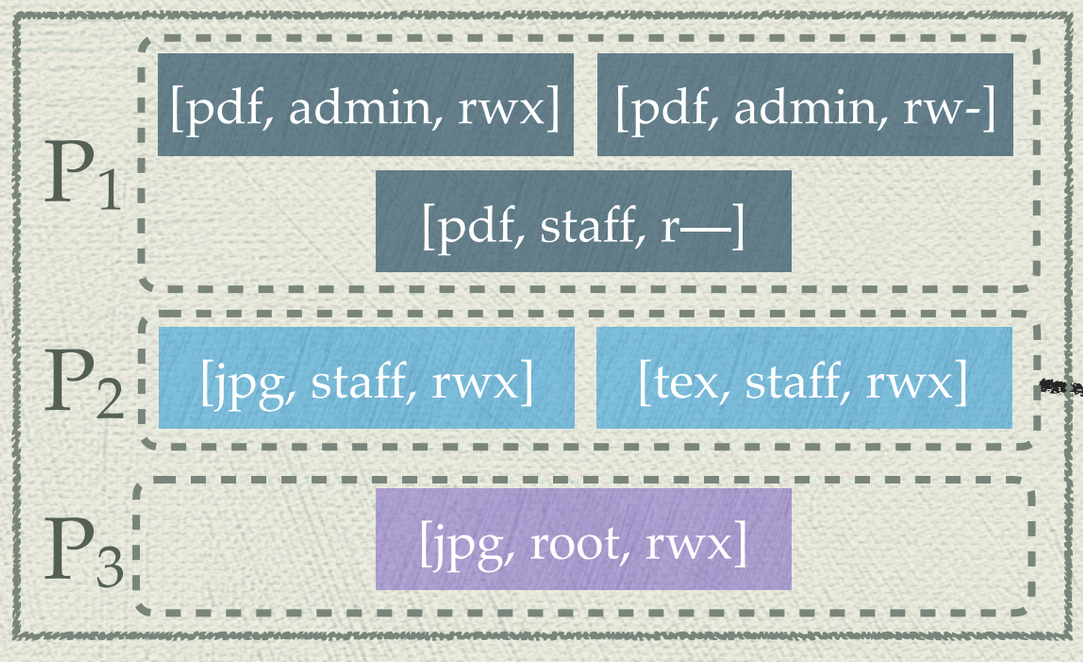
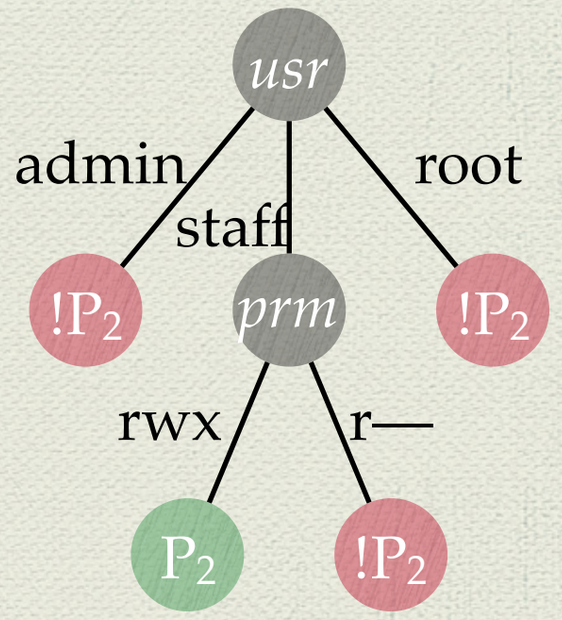




Feature set: [extension, user, permissions]

(*user* = staff) &&
(*permissions* = rwx)

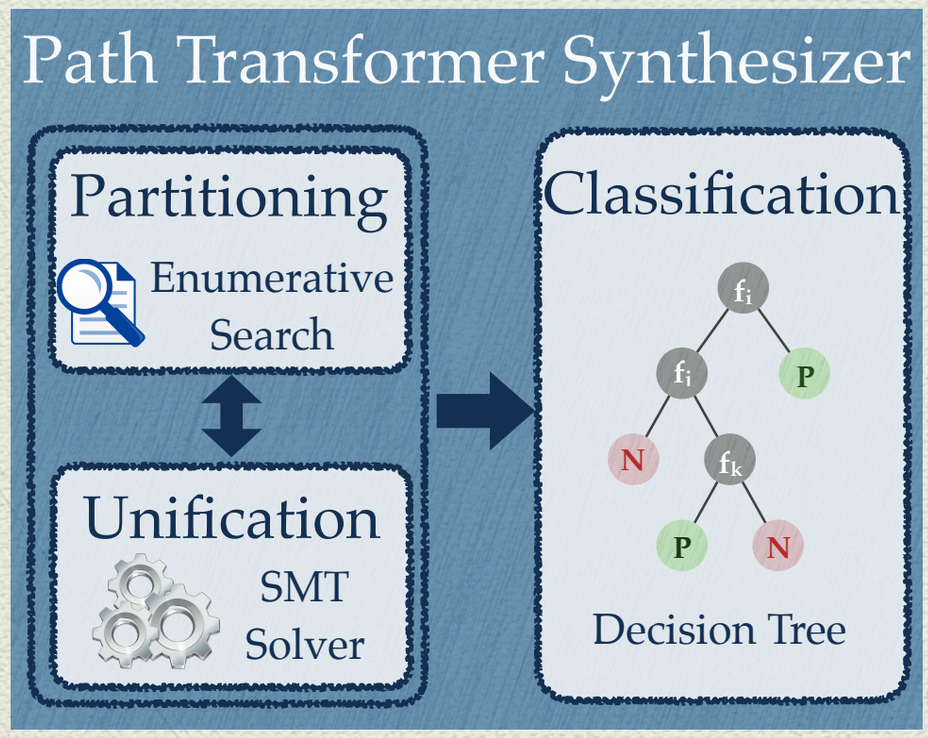
Technical Contributions

- Reduction of tree transformation synthesis to path transformation synthesis

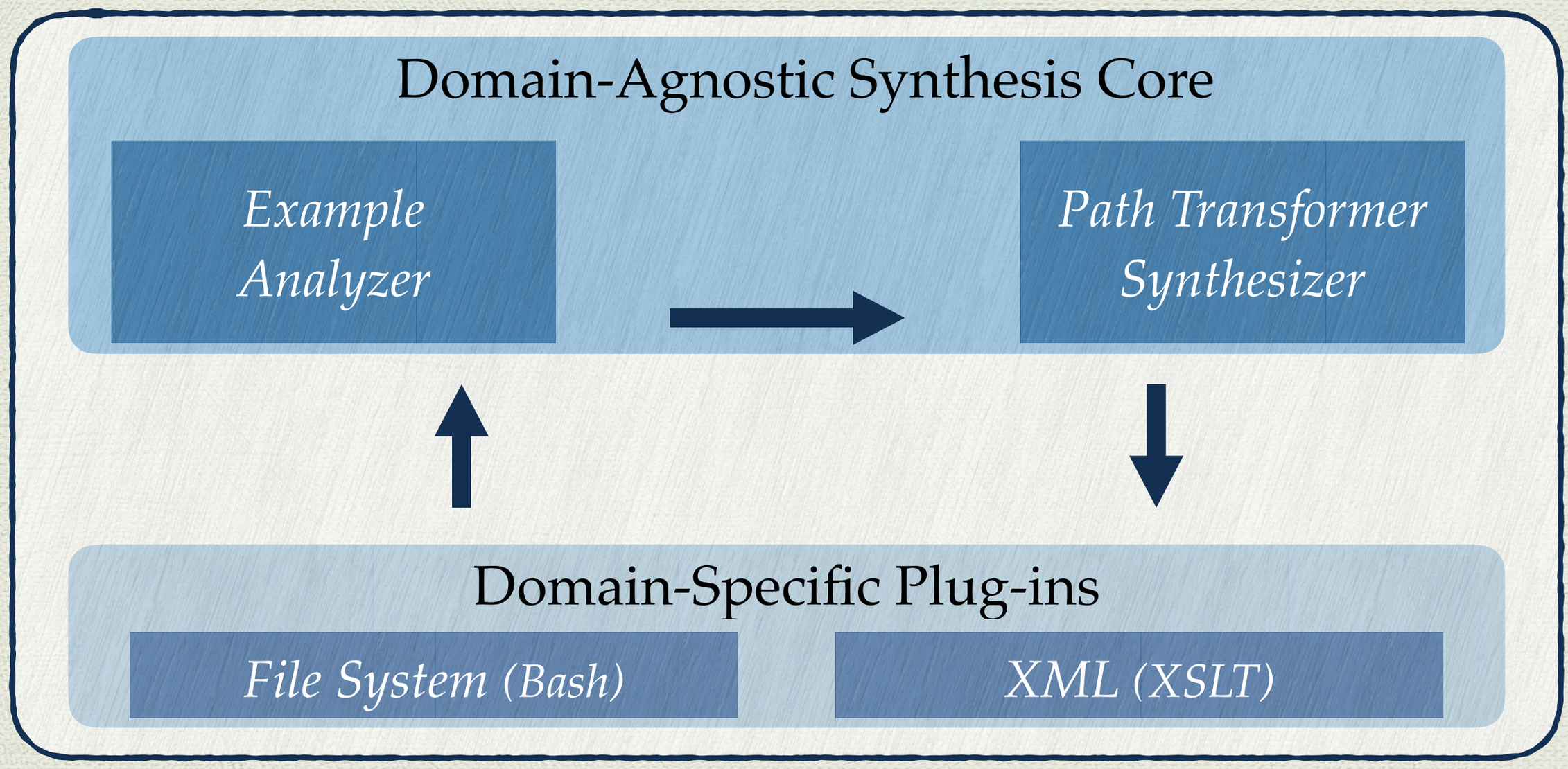
Technical Contributions

- Reduction of tree transformation synthesis to path transformation synthesis

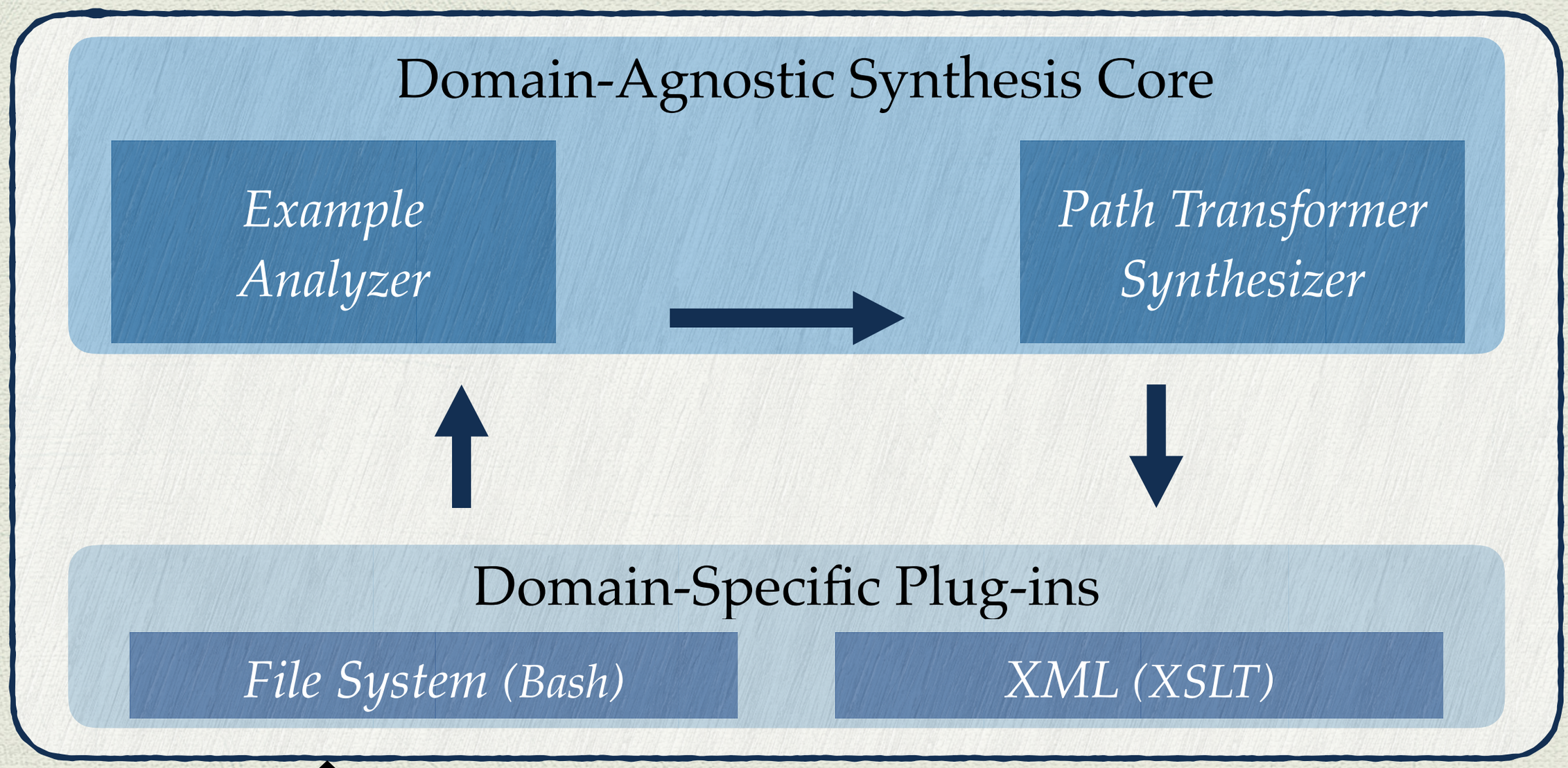
- New algorithm for path transformation synthesis based on:
  - **Enumerative Search**
  - **SMT Solving**
  - **Decision Tree Learning**

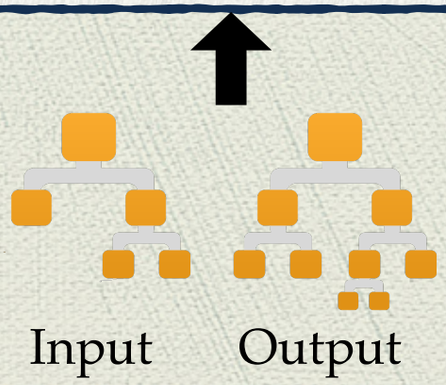


HADES Design

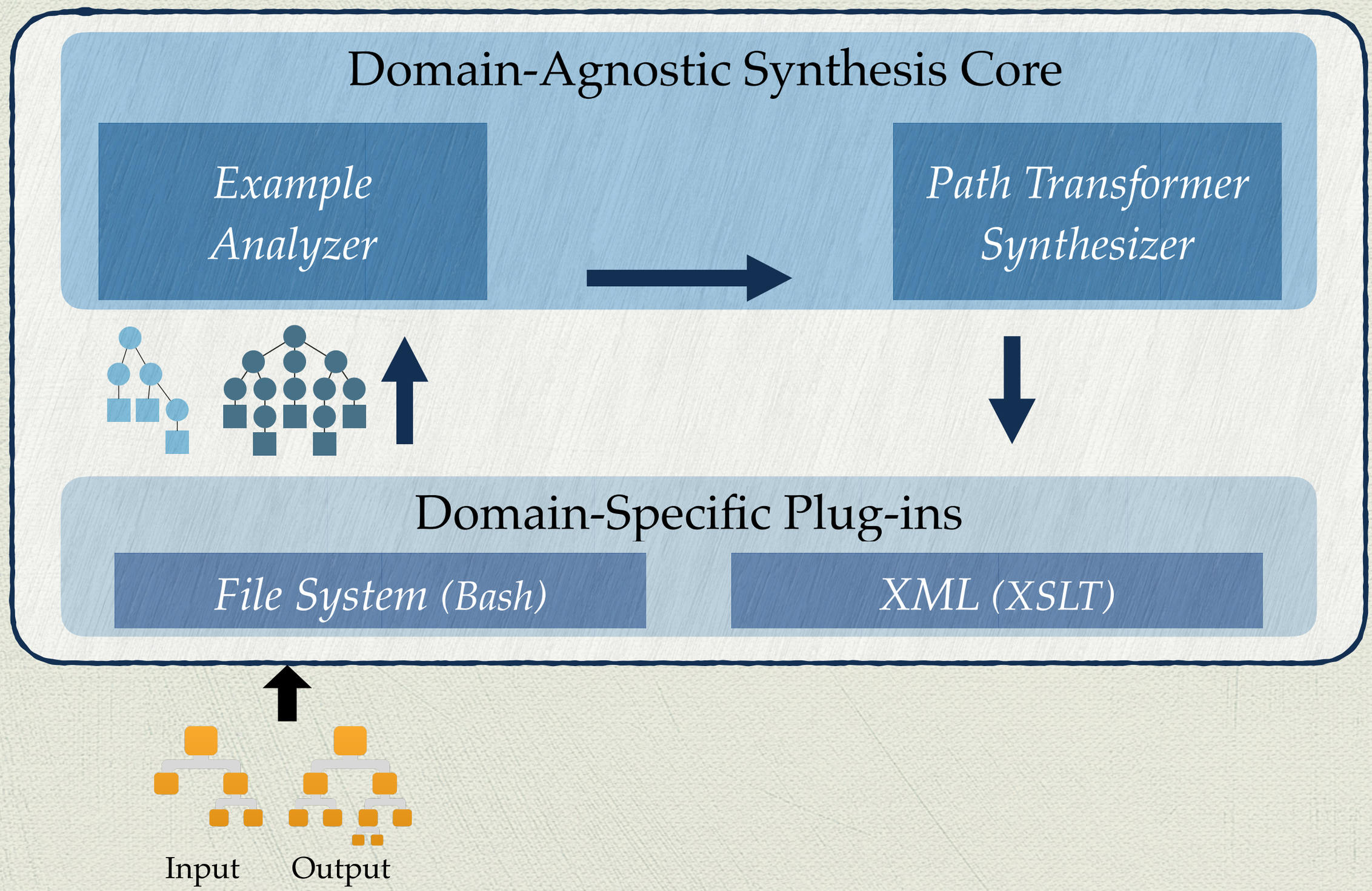


HADES Design





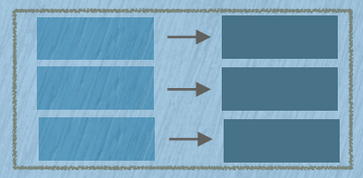
HADES Design



HADES Design

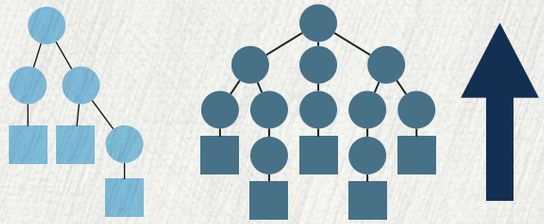
Domain-Agnostic Synthesis Core

Example Analyzer



Path Examples

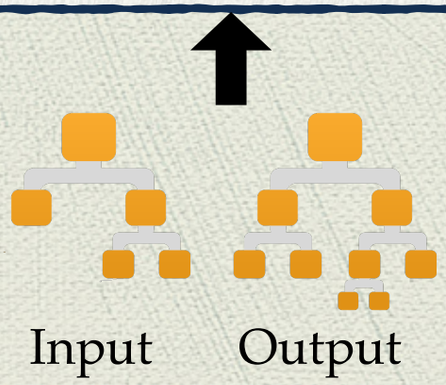
Path Transformer Synthesizer



Domain-Specific Plug-ins

File System (Bash)

XML (XSLT)

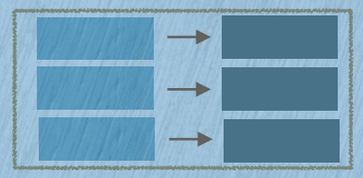


Input Output

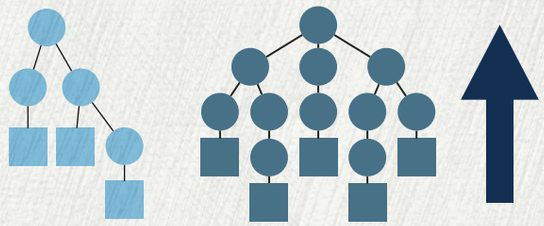
HADES Design

Domain-Agnostic Synthesis Core

Example Analyzer



Path Transformer Synthesizer



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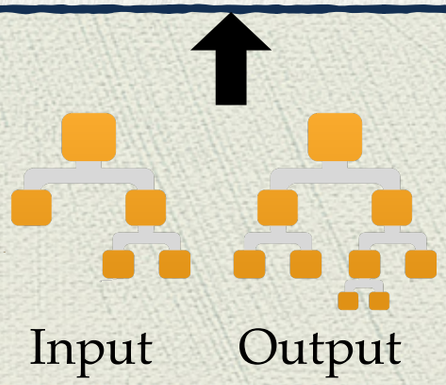
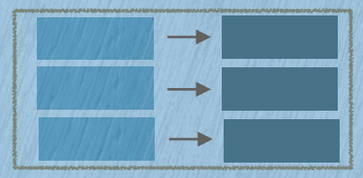


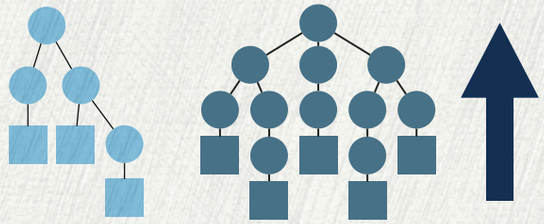
HADES Design

Domain-Agnostic Synthesis Core

Example Analyzer



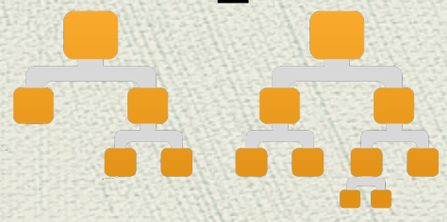
Path Transformer Synthesizer



Domain-Specific Plug-ins

File System (Bash)

XML (XSLT)



Input Output

Executable code

Demo

Evaluation Criteria

Expressiveness

Performance

Usability

Evaluation Criteria

Expressiveness

Can it synthesize transformations for real-world tasks?

Performance

Usability

Evaluation Criteria

Expressiveness

Can it synthesize transformations for real-world tasks?

Performance

How long does it take to synthesize the desired transformation?

Usability

Evaluation Criteria

Expressiveness

Can it synthesize transformations for real-world tasks?

Performance

How long does it take to synthesize the desired transformation?

Usability

How many rounds of user interaction does it need?

Evaluation Setup

- Collected **36** benchmarks: **24** *File System* and **12** *XML*
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- All experiments conducted on a commercial MacBook.

Results

Expressiveness

Synthesized the desired transformation for **all benchmarks**

Performance

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Less than **one second** for **91.6%** of benchmarks
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Usability

88.8% of benchmarks require only **1 or 2 rounds** of user interaction

Example complexity: 1 input-output tree with 4 leaves (avg)

Conclusion

- A general approach for tree transformation synthesis.
- Can synthesize a broad class of transformations which alter the tree structure.
- Promising results on real-world synthesis tasks.