Towards Family-Based Vulnerability Discovery for Highly-Configurable Software Systems

Meeting on Feature-Oriented Software Development 2026, Odense

Tim Bächle, Erik Hofmayer, Tobias Pett, Ina Schaefer | 24th March 2026

Test, Validation, Analysis

Context

```
1  void foo() {
2      int x = source(); // Attacker-controlled.
3      if(x < MAX){ // Does not enforce x >= 0.
4          int y = 0;
5  #ifdef CONFIG_PROCESS_INPUT
6          y = 2 * x;
7      #ifdef CONFIG_SEND_DATA
8          sink(y); // Security-sensitive operation.
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11         // ...
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A configurable C function adapted from the example provided by Yamaguchi et al. [Yam+14]

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A **vulnerability** that is **present in some but not all variants** derivable from a configurable software system [Bäc+25].

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Popular Analysis Strategies [Thü+14]

- **Product-Based**: Derive variants and analyze them individually
- **Family-Based**: Analyze a configurable system as a whole

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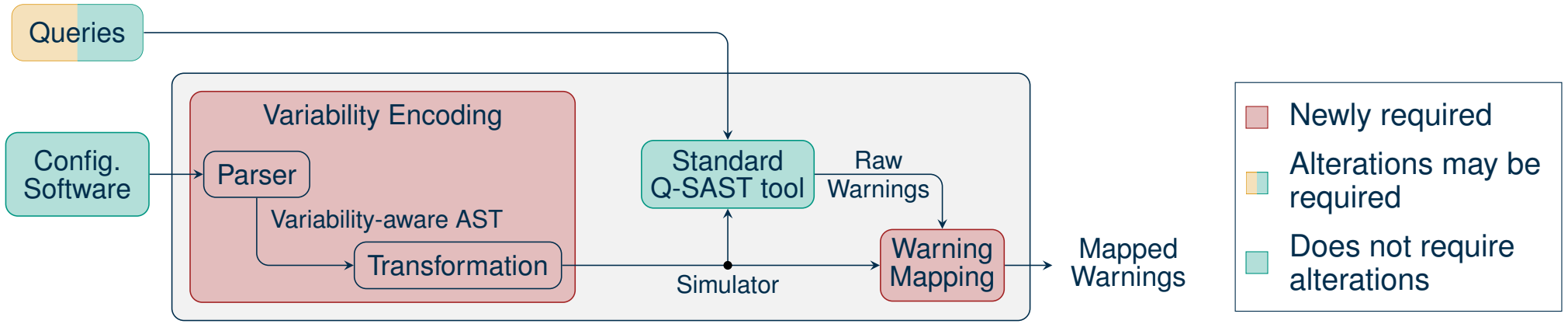
Family-Based Analysis

- \+ Promises **Completeness** [Ape+13; Lie+13; von+18]
- \+ Promises **Scalability** [Ape+13; Lie+13; von+18]
- ϟ Static **analysis tools** typically **cannot cope with variability** [Fer+16; Pat23; Sch+22]

How can we change that for query-based (Q-SAST) tools?

Lifting Strategies [los+17; Pat23; Thü+12; von+16]

Lifting by Simulation



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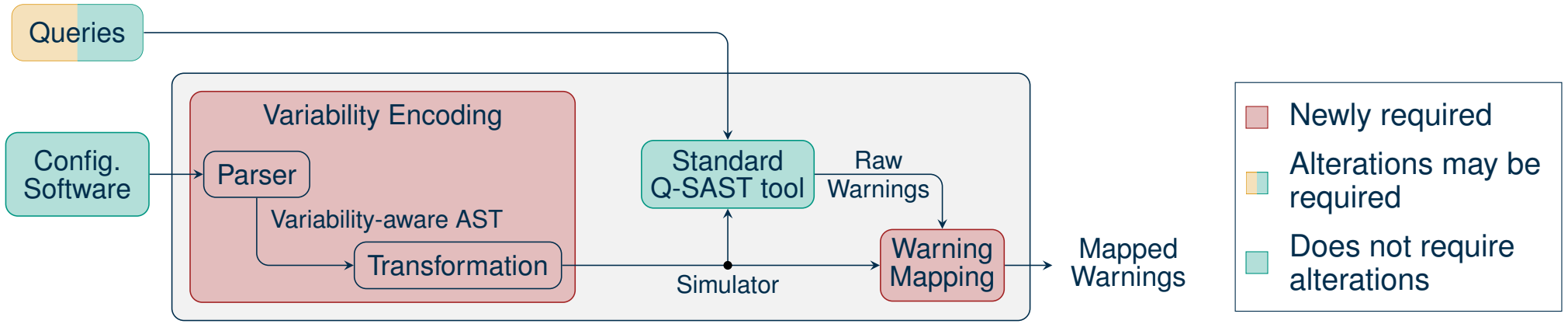
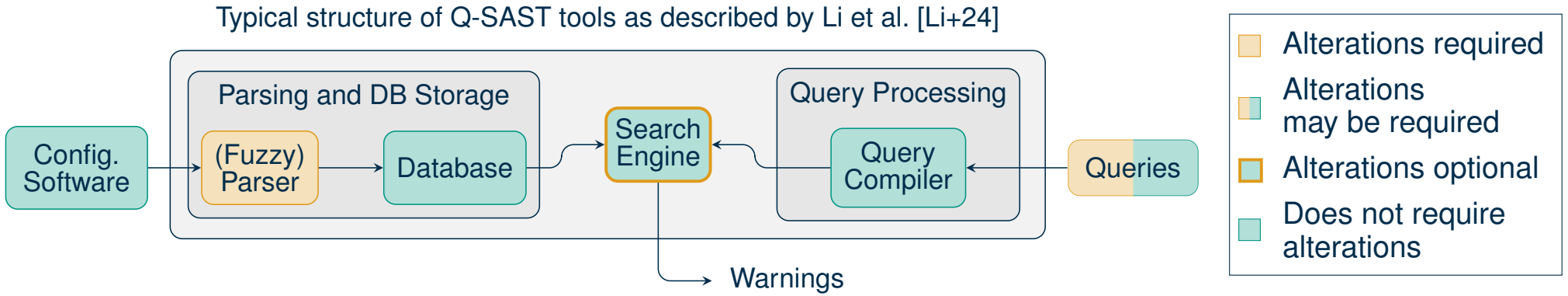


Lifting by Extension



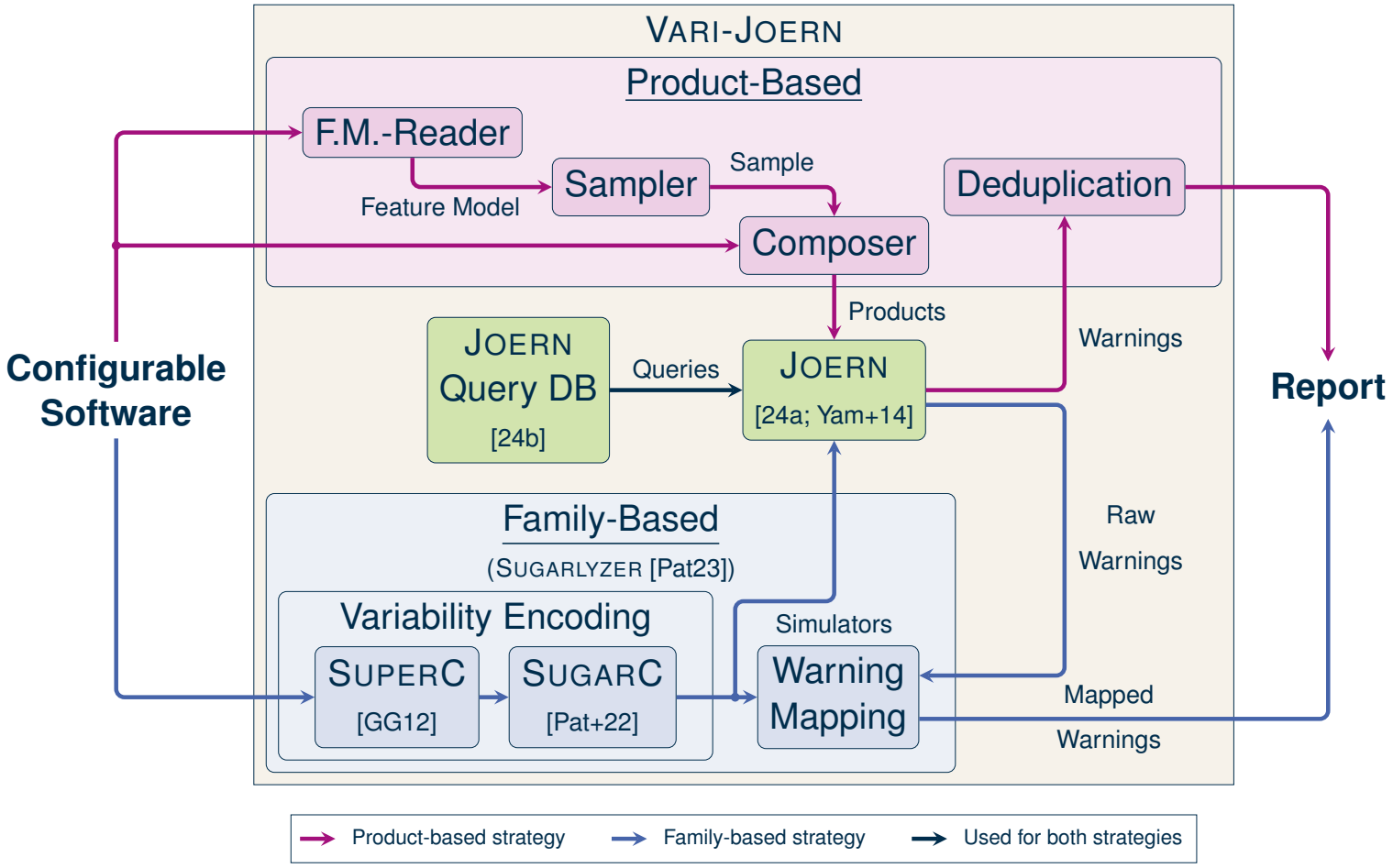
Implementing Lifting by Simulation

Idea

- **Extend VARI-JOERN** [Bäc+25] with a family-based analysis strategy based on lifting by simulation
- **Realized using SUGARC** by Patterson et al. [Pat+22] for variability encoding

Evaluation

- **Compare the capabilities** between product- and family-based vulnerability discovery



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Comparison of vulnerability warnings between product-based (PB) and family-based (FB) analysis:

System	t	Share Type 1	Share Type 2	Share Type 3	Total
AXTLS	2, 3	95.28% (1010)	0.94% (10)	3.77% (40)	1060
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BUSYBOX	2	34.59% (4991)	59.82% (8632)	5.60% (808)	14431
	3	34.76% (5019)	59.83% (8639)	5.41% (781)	14439

Type 1: Both PB and FB Type 2: Only PB Type 3: Only FB

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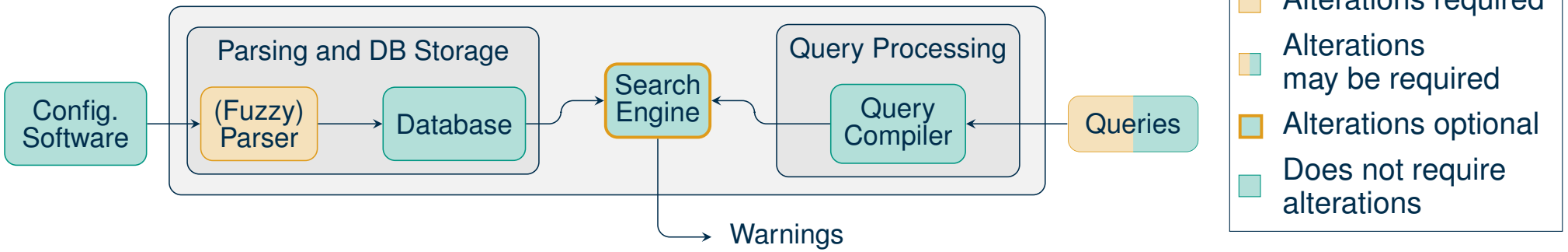
Main reason for Type 2: **Limitations of variability encoding**

Implementing Lifting by Extension

Challenges

Typical structure of Q-SAST tools as described by Li et al. [Li+24]



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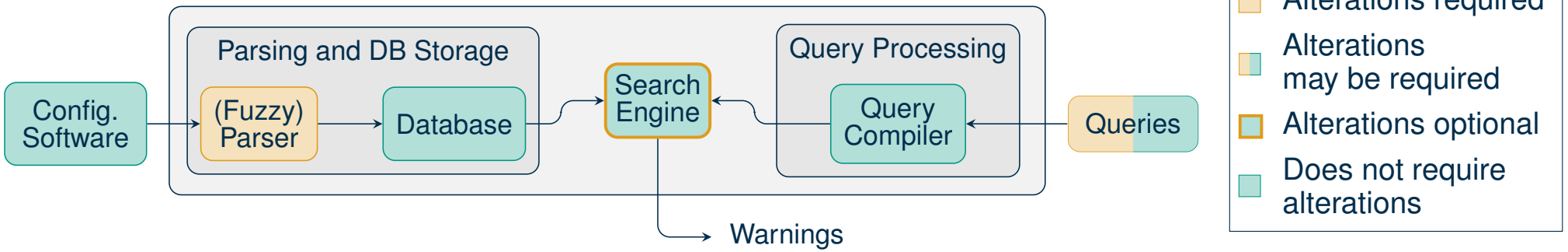

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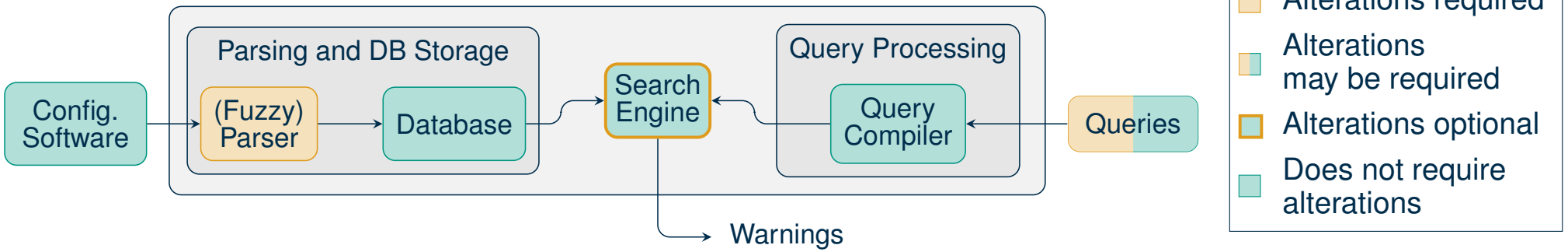

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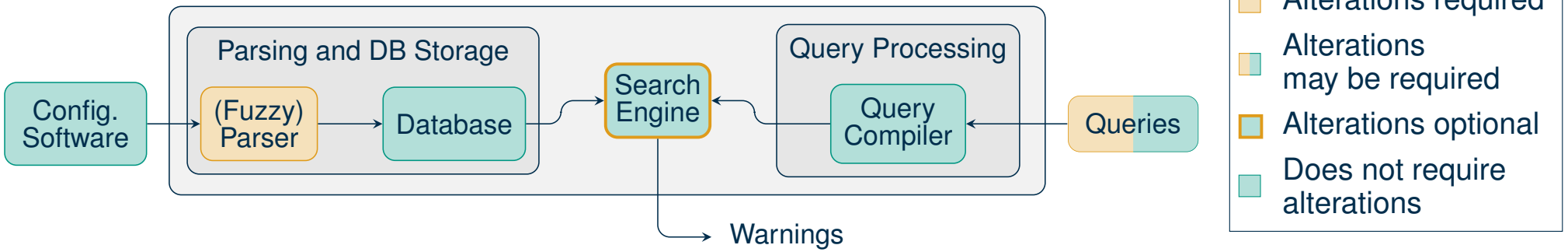

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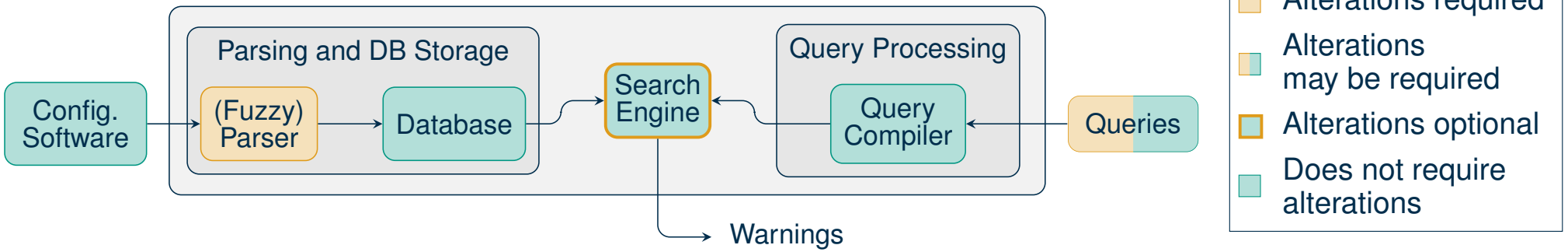

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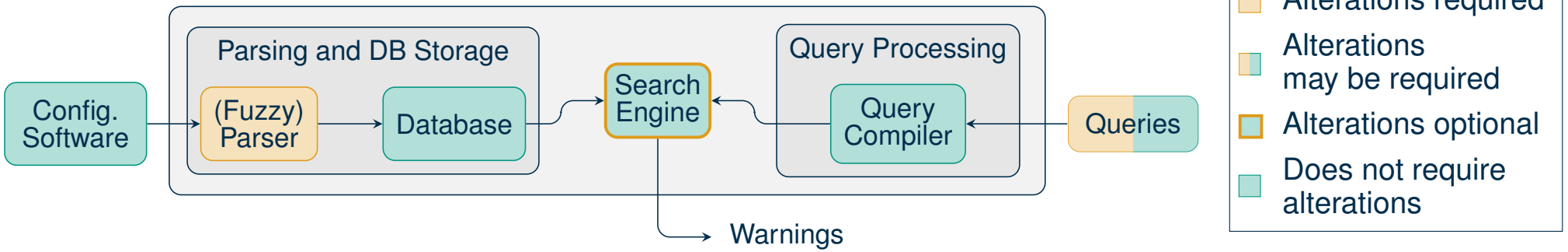

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Implementing Lifting by Extension

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- JOERN uses **Code Property Graphs (CPGs)** as underlying data structure [Yam+14]
- A **CPG combines** a program's:
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- Two popular options:
  - Dedicated **choice nodes** [GG12]
  - Edges with **presence condition labels** [Ken+10; Lie+13]

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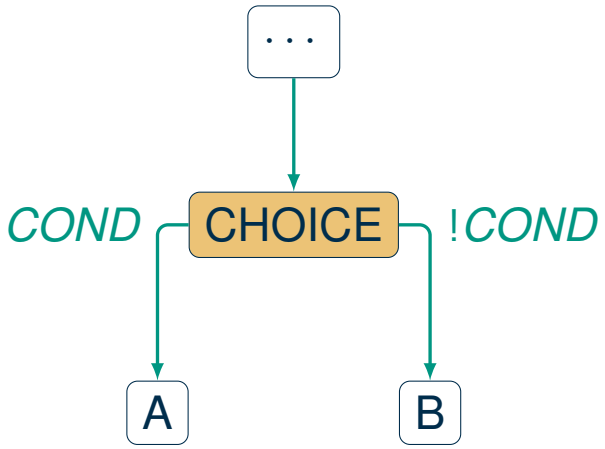
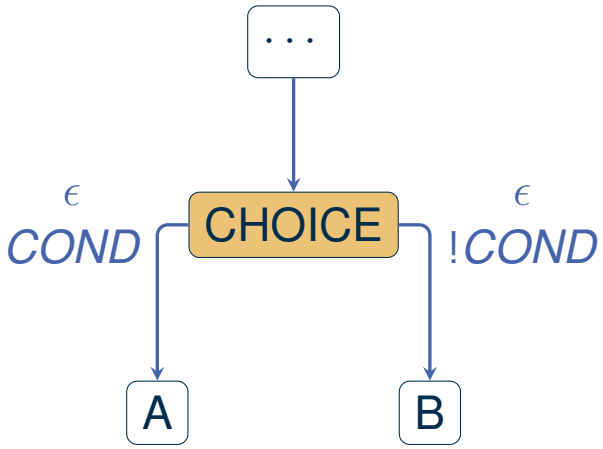
Abstract Syntax Tree



Control Flow Graph



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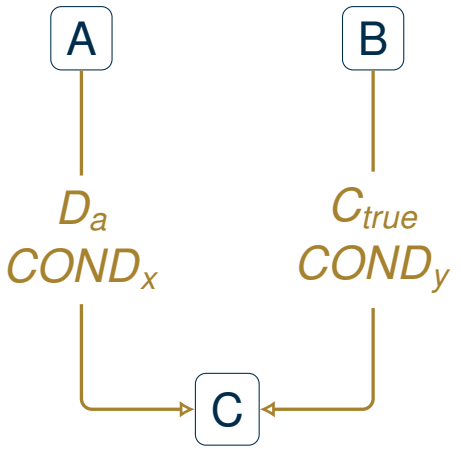

Implementing Lifting by Extension

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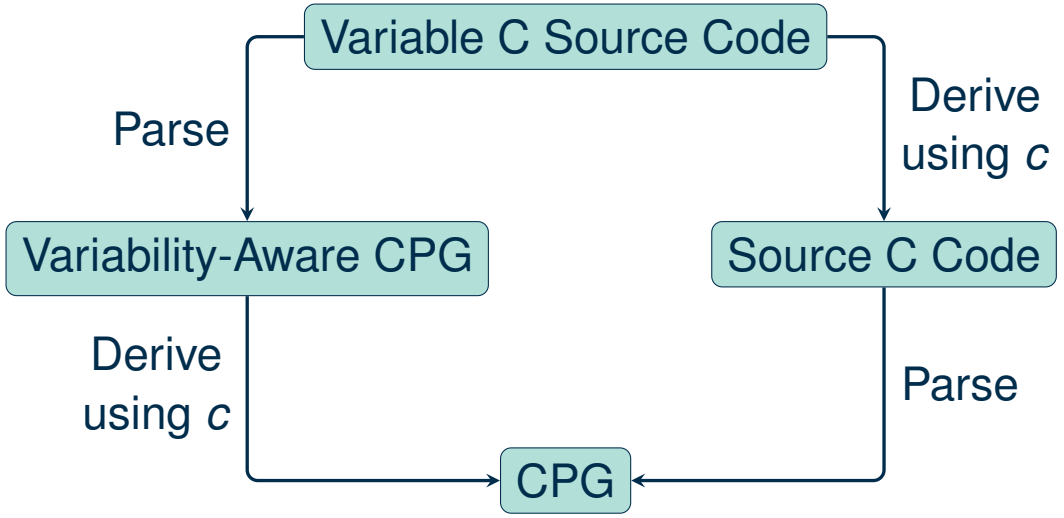
A Note on Correctness

- **Ideally**, we would show that the **commuting diagram holds**
- Intuition suggests this
- A formal proof has yet to be performed



For arbitrary variable source code and an arbitrary (but valid) configuration *c*

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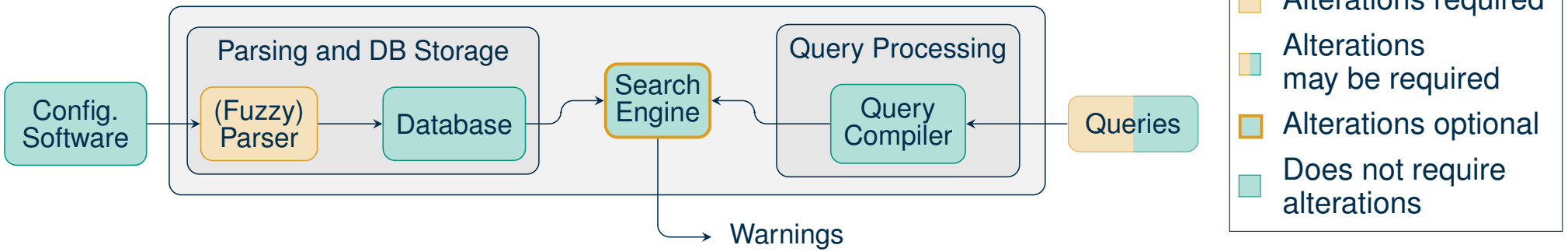

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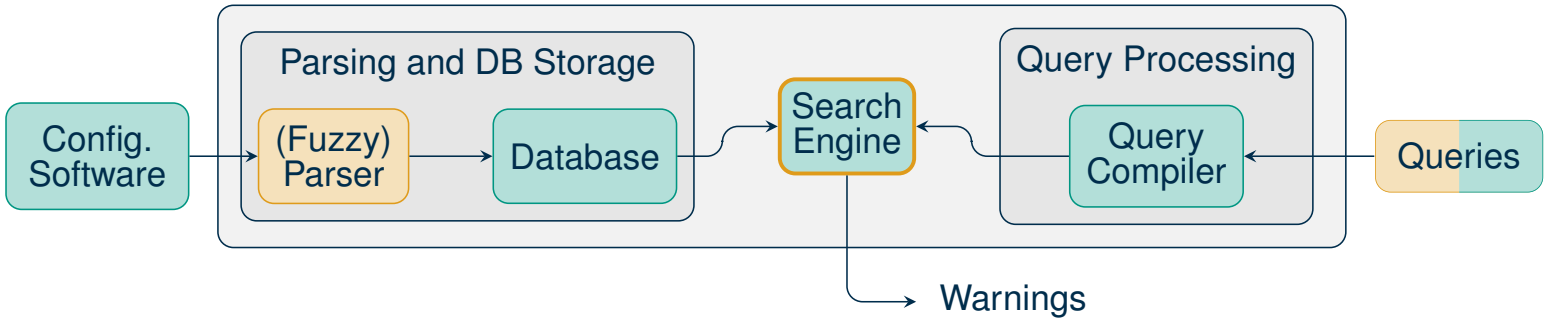

- Alterations required
- Alterations may be required
- Alterations optional
- Does not require alterations

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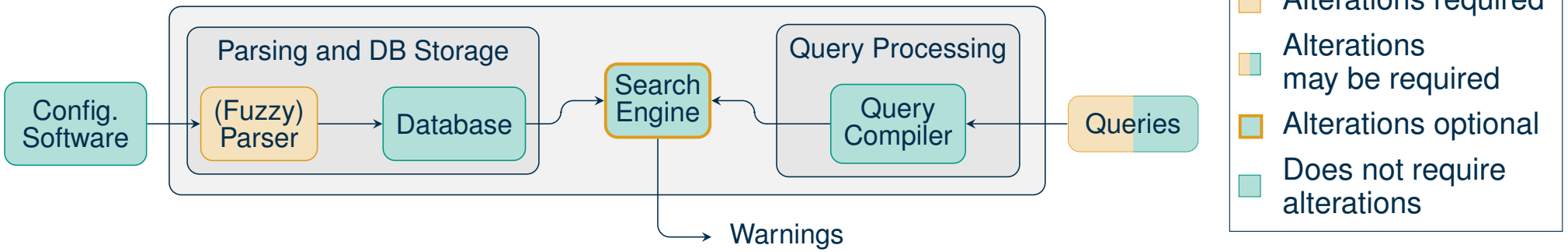

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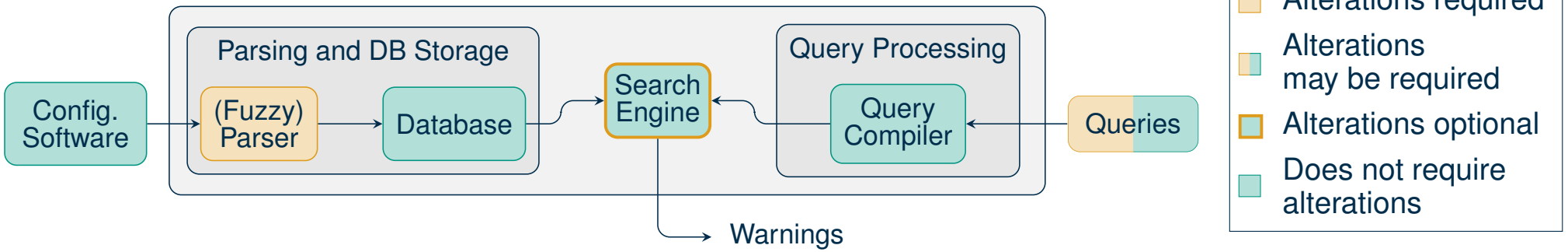

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- JOERN already has a front end for parsing C into a CPG
- This front end is variability-oblivious

⇒ Can we make it variability-aware (i.e., capable of building a VA-CPG)?

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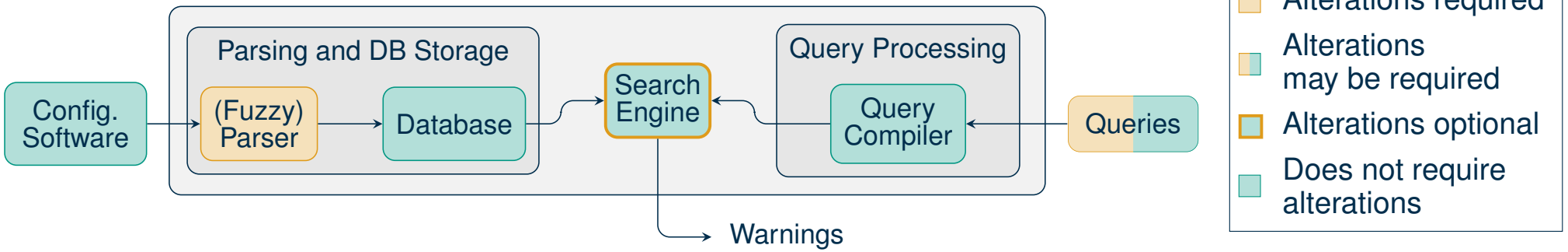

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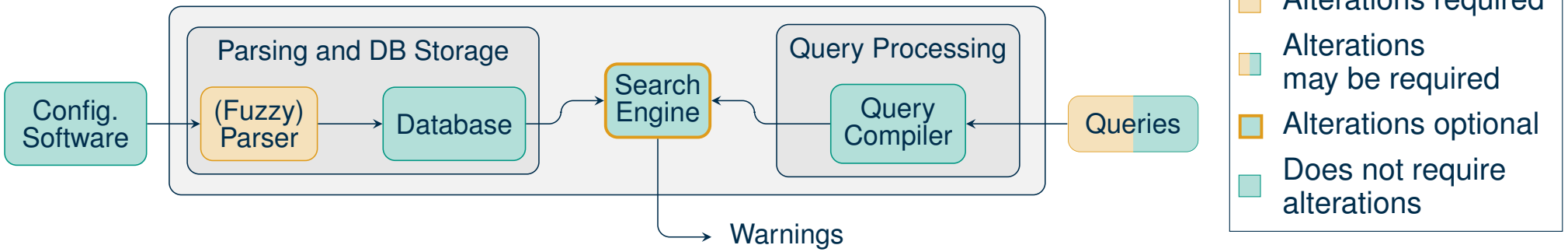

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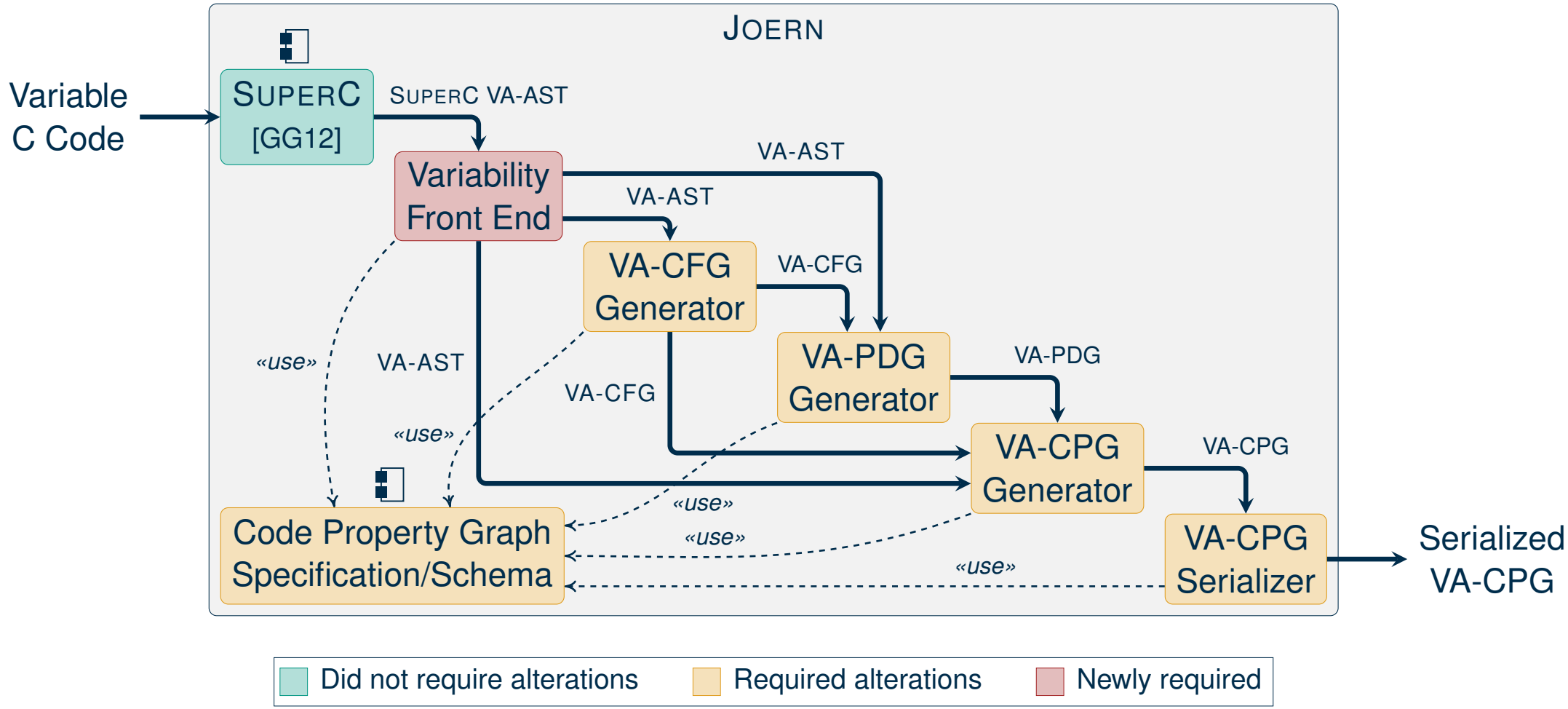

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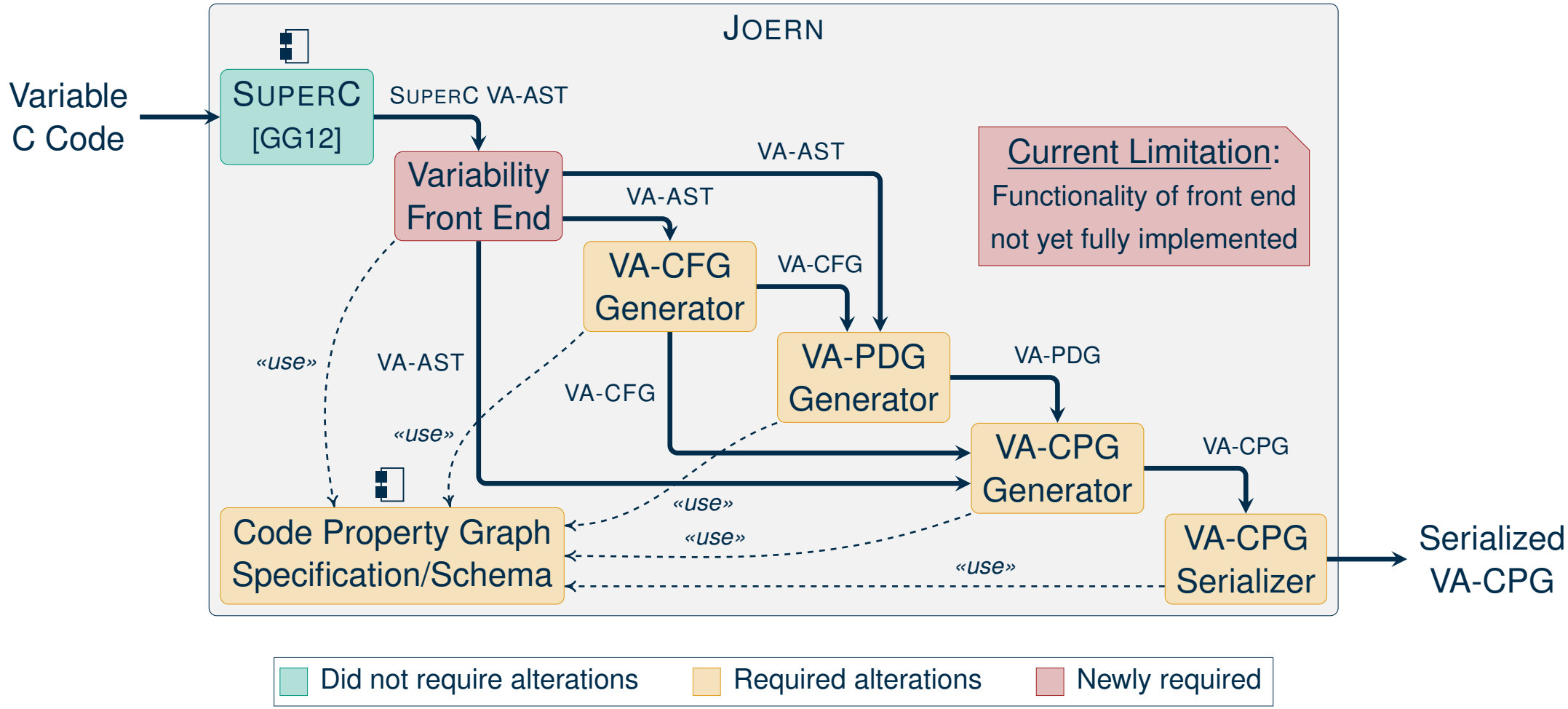

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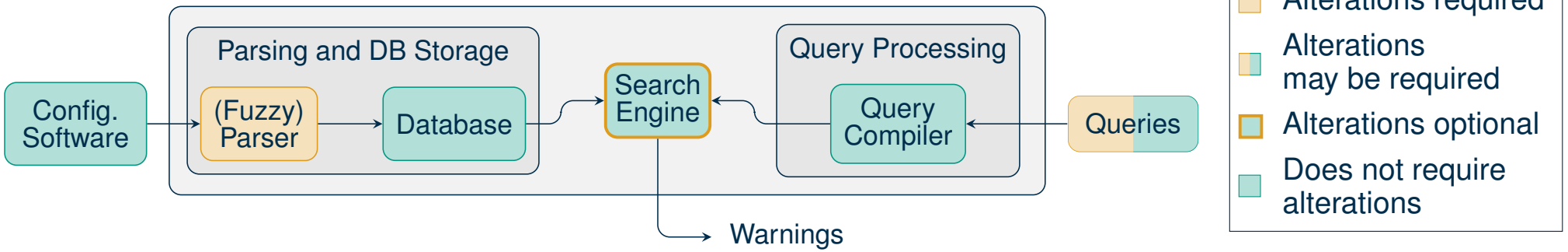

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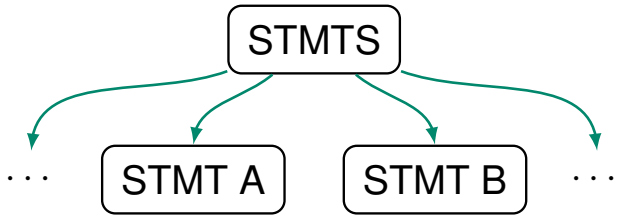
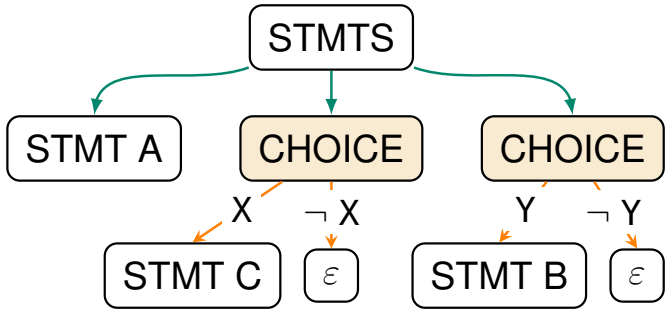


The pattern occurring in a variability-aware AST:



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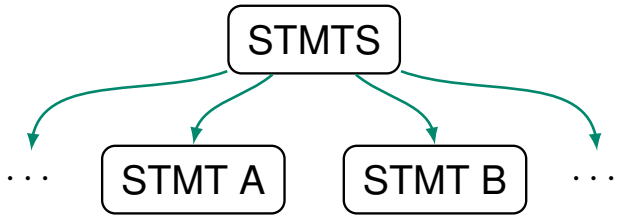

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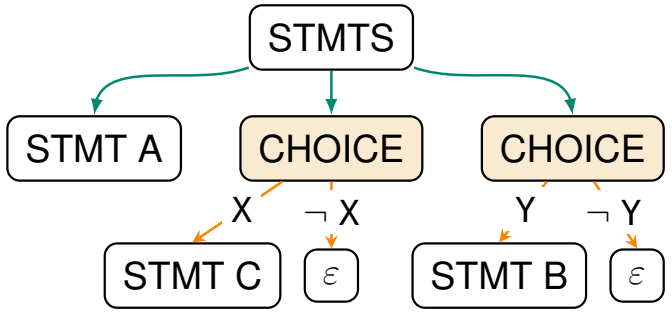

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Variability-Oblivious Queries

- Do not take variability into account
- \+ Easy to specify (existing queries can be reused)
- − Can lead to false negatives due to variability

Variability-Aware Queries

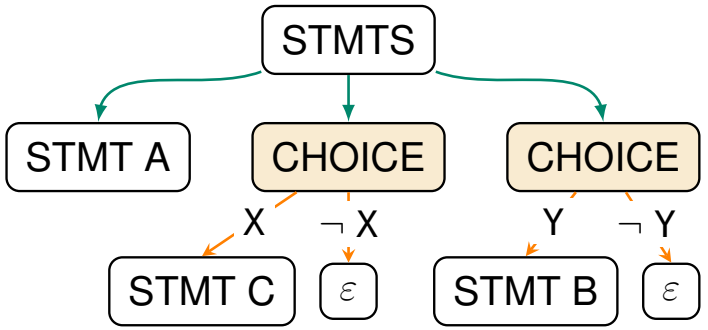
- Take variability into account
- \+ Can avoid false negatives
- − Harder to specify (user has to be aware of variability)

Implementing Lifting by Extension

3. Querying — Possible Solutions

Adjusting the Queries

- Some queries are not affected by variability
  ⇝ `(cpg.method("(?i)gets").callIn).l`
- Others might need to be made variability-aware



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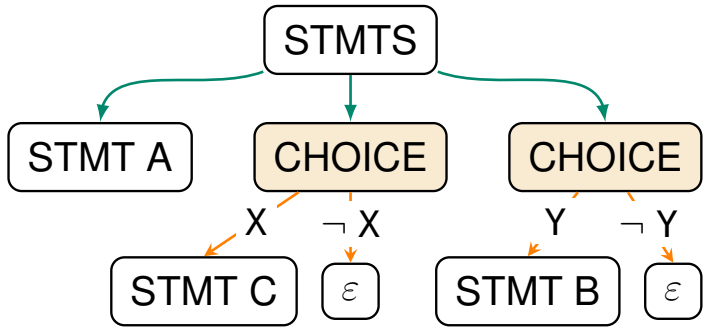
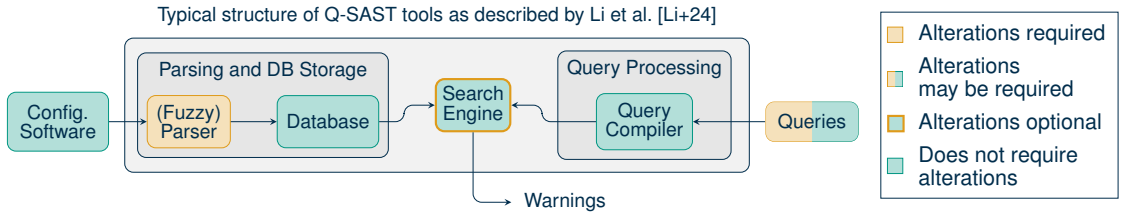
Adjusting the Search Engine

- Make search engine aware of variability (e.g., via choice nodes)
- Would avoid having to adjust certain queries





Implementing Lifting by Extension

3. Querying — Possible Solutions

Adjusting the Queries

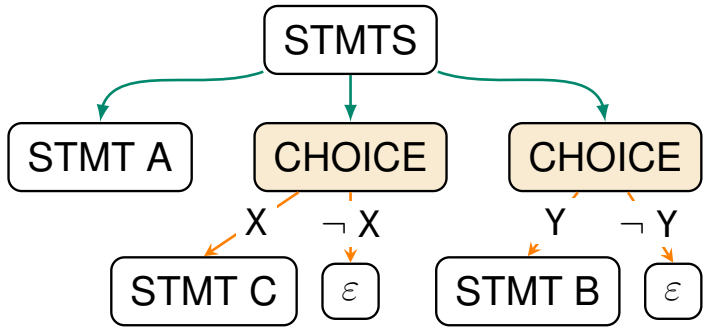
- Some queries are not affected by variability
  ⇝ `(cpg.method("(?i)gets").callIn).l`
- Others might need to be made variability-aware

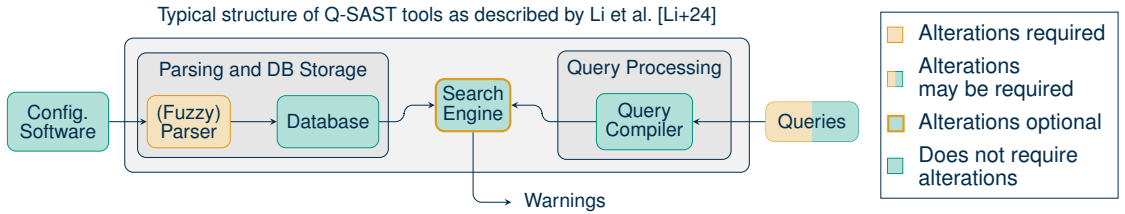
Adjusting the Search Engine

- Make search engine aware of variability (e.g., via choice nodes)
- Would avoid having to adjust certain queries

Preprocessing Queries

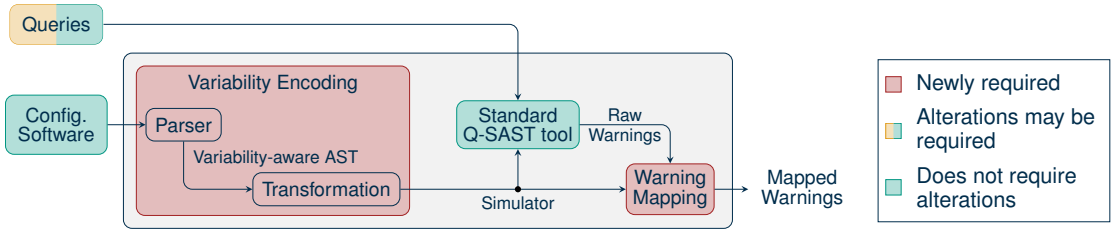
- Adjusting queries and / or search engine is tedious
- Can we make queries variability-aware by preprocessing them?





Summary

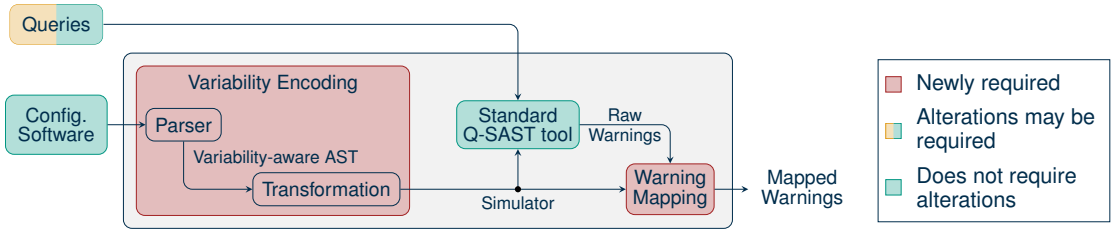
Lifting by Simulation



- ⊕ Low implementation effort and independent of tool
- ⊖ Additional analysis effort and potential imprecision

Summary

Lifting by Simulation



- ⊕ Low implementation effort and independent of tool
- ⊖ Additional analysis effort and potential imprecision

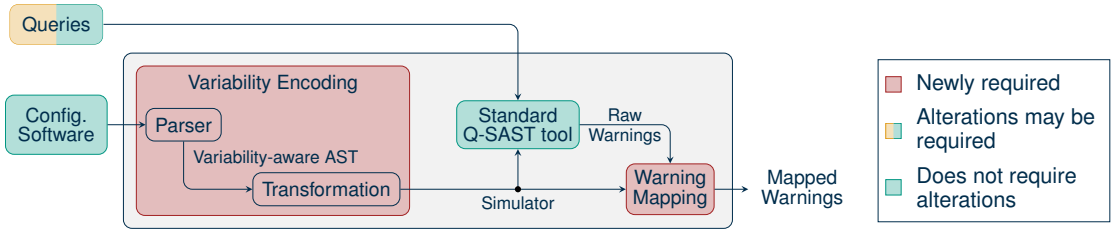
System	t	Share Type 1	Share Type 2	Share Type 3	Total
axTLS	2, 3	95.28% (1010)	0.94% (10)	3.77% (40)	1060
Toybox	2, 3	78.83% (5770)	14.75% (1080)	6.42% (470)	7320
BusyBox	2	34.59% (4991)	59.82% (8632)	5.60% (808)	14431
	3	34.76% (5019)	59.83% (8639)	5.41% (781)	14439

Type 1: Both PB and FB Type 2: Only PB Type 3: Only FB

Main reason for Type 2: **Limitations of variability encoding**

Summary

Lifting by Simulation



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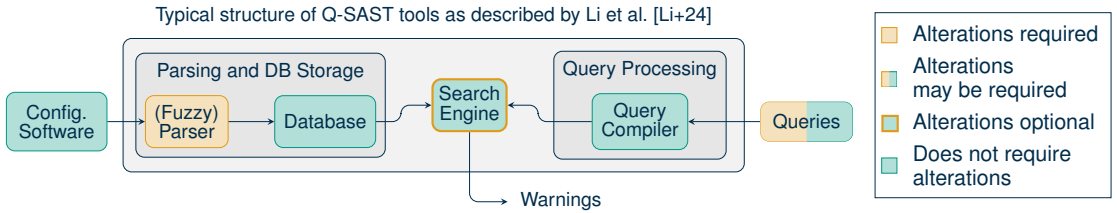
Lifting by Extension

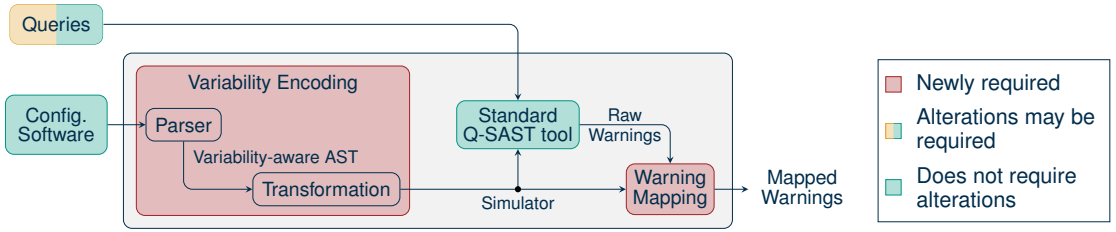


⊕ Precision and Performance?

⊖ Tool-specific and implementation labor-intensive

Summary

Lifting by Simulation



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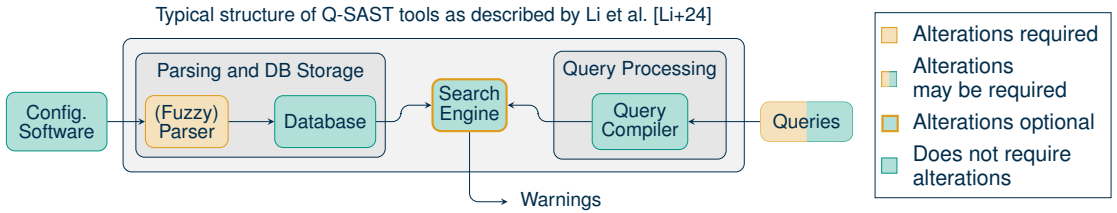

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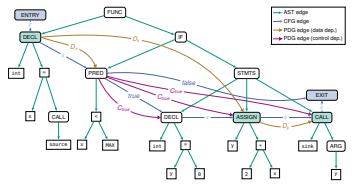
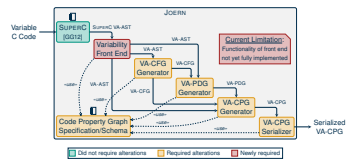
⊖ Tool-specific and implementation labor-intensive

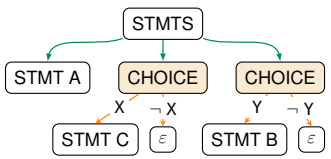
1. Var.-Aware Data Structure



2. Parsing



3. Querying



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