Precise and Scalable Detection of Use-after-Compacting-Garbage-Collection Bugs

HyungSeok Han, Andrew Wesie, Brian Pak

Theori Inc.

Garbage Collection (GC)

- Automatic memory management system.

.NET

...

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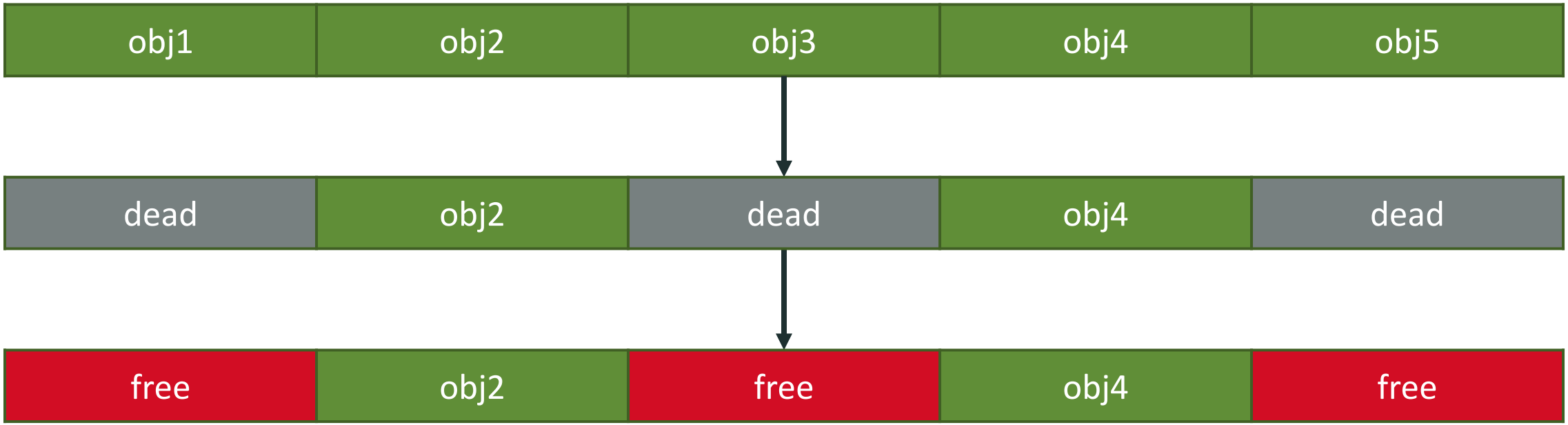
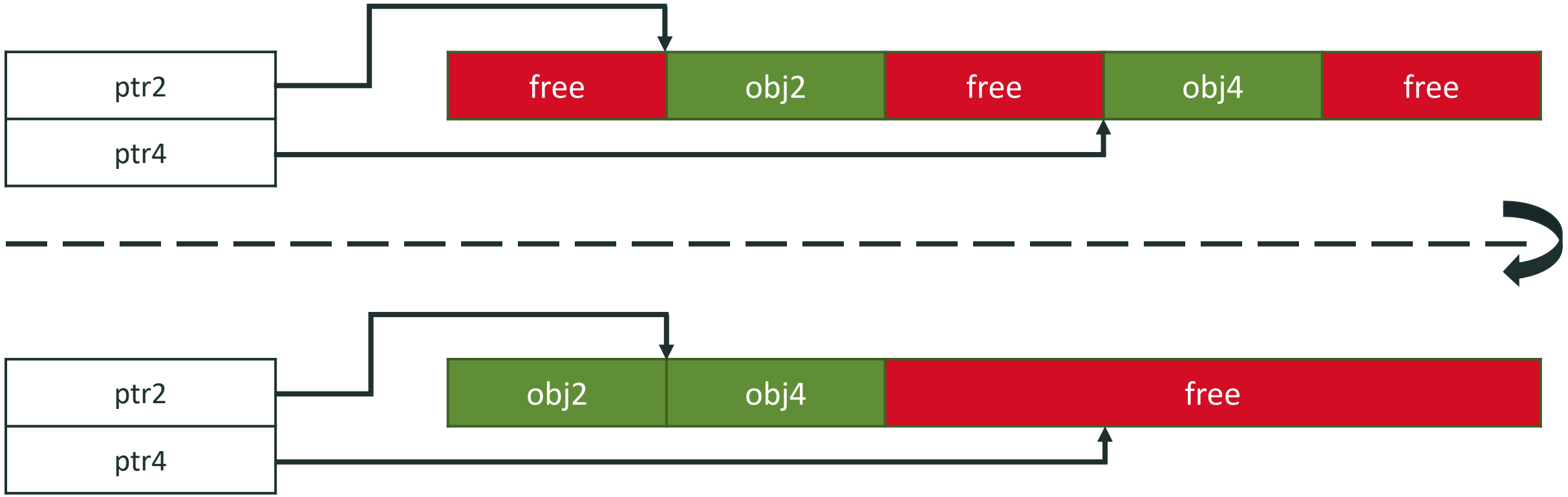


Memory fragmentation

Compacting GC (CGC)

- Mitigate memory fragmentation by rearranging live memory objects.



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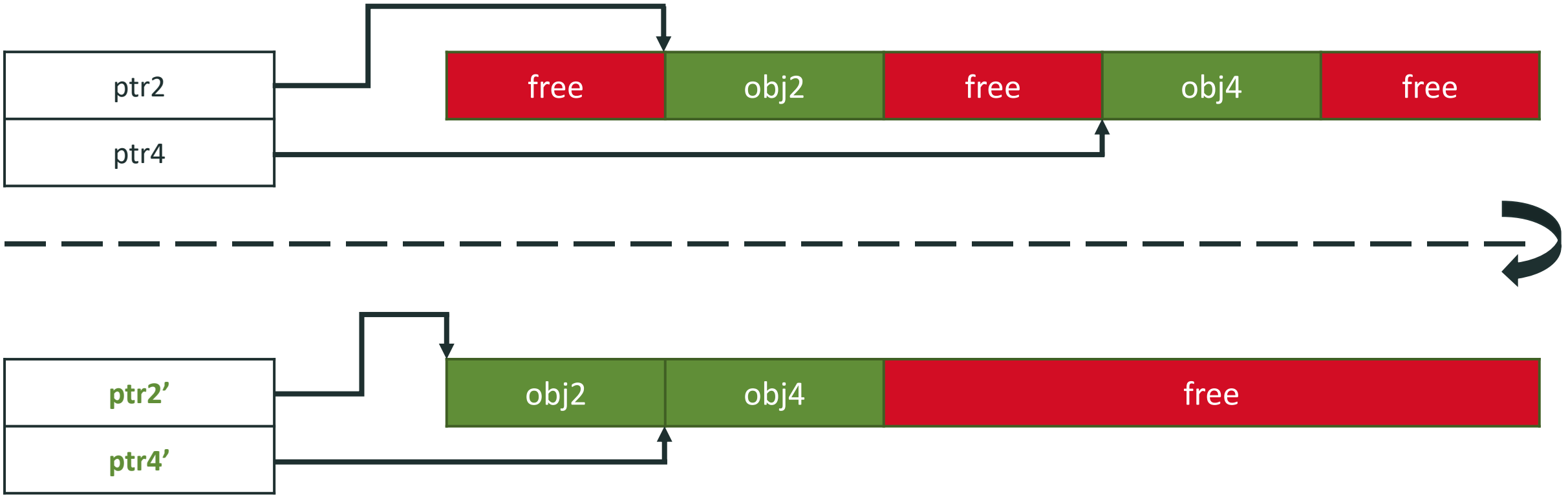
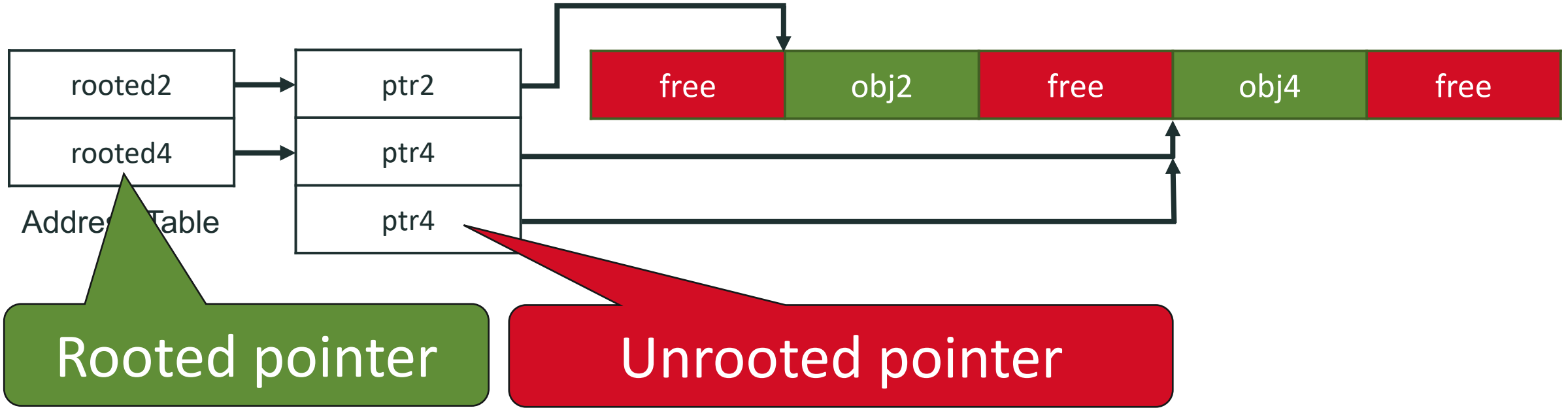


Compacting GC (CGC)

- To update references, it manages an address table containing memory addresses where the references are stored.



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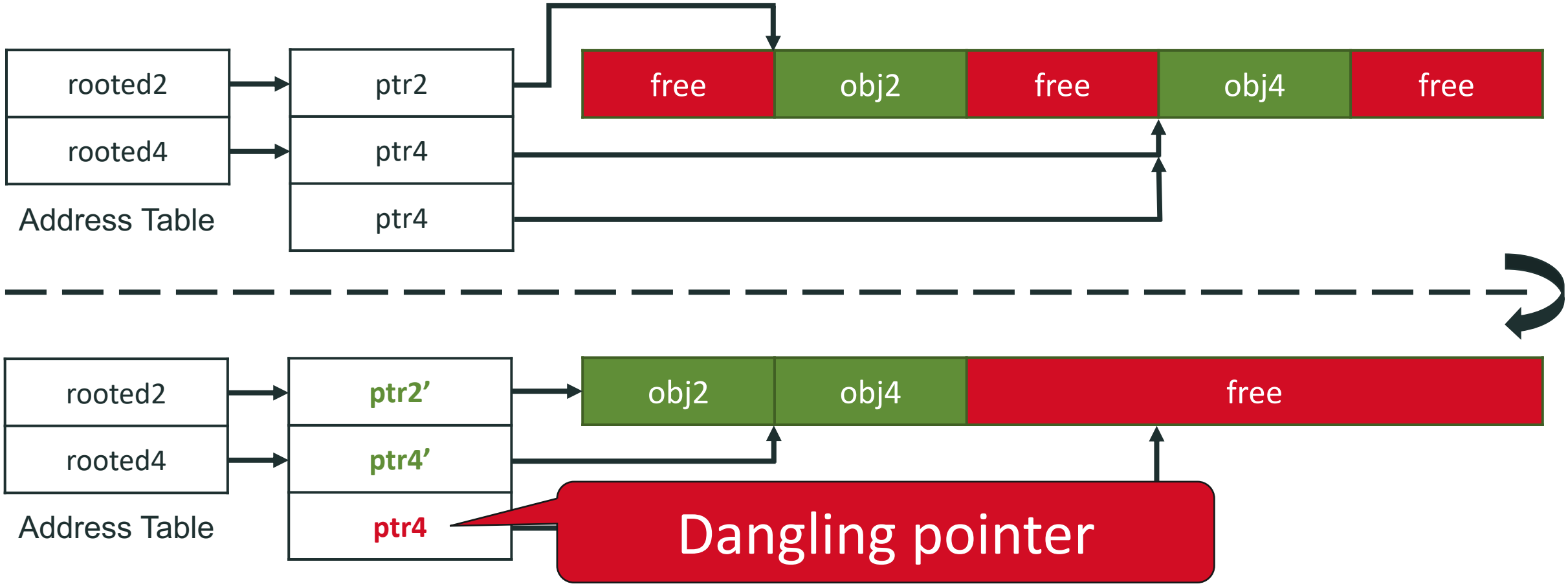

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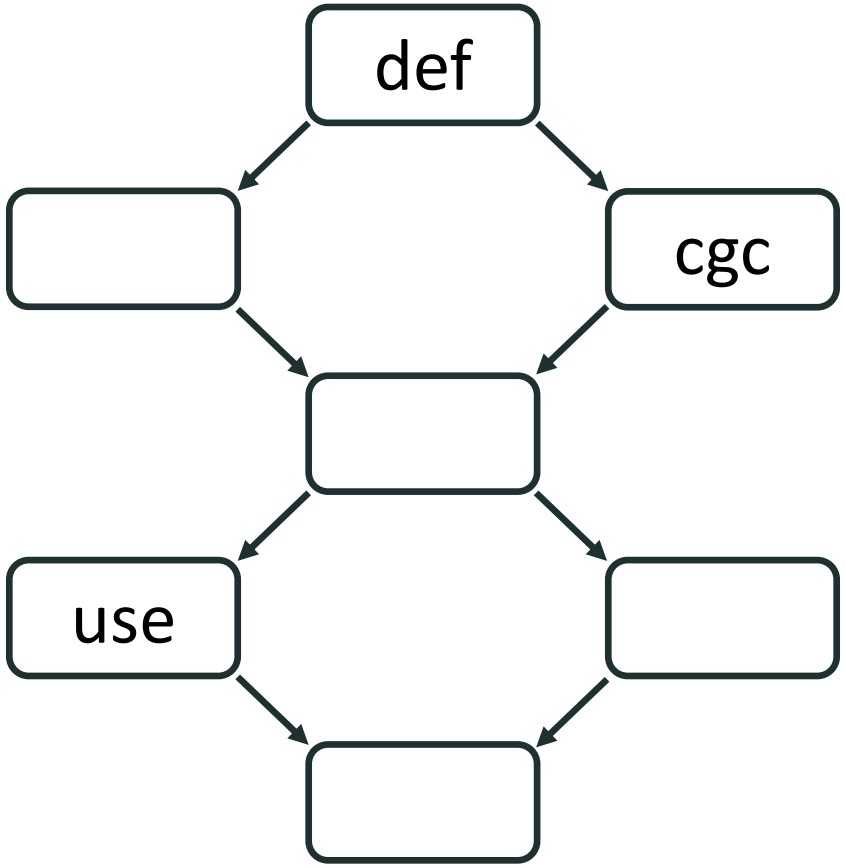

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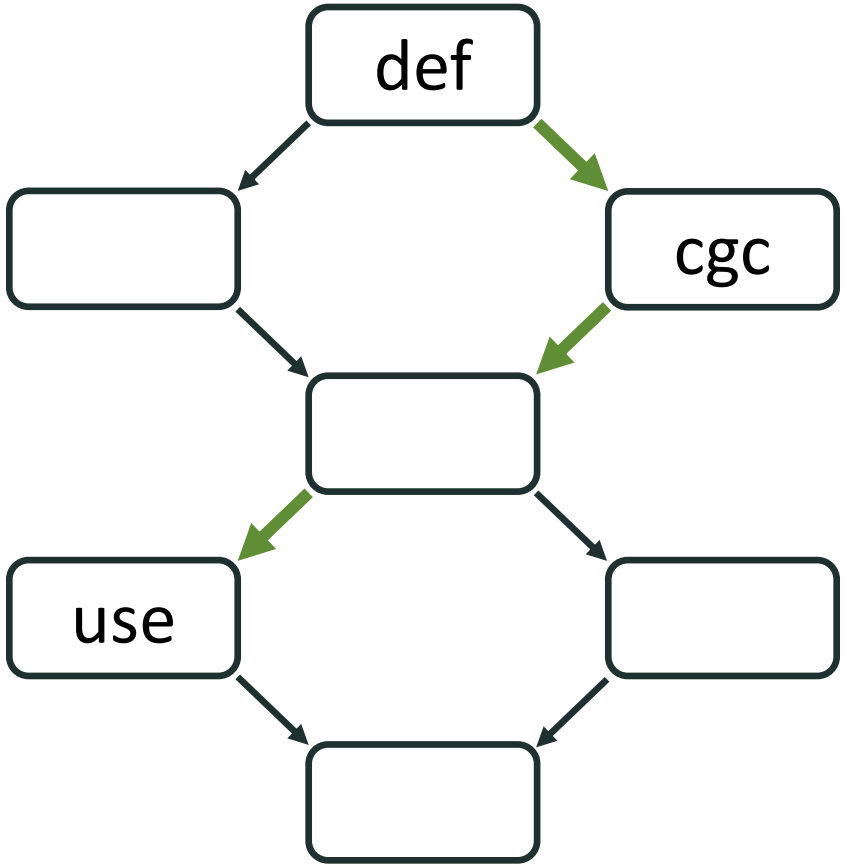

Example (CVE-2019-13696)

```
void InterpretedFrame::Summarize(...) const {
  ...
  // define an unrooted pointer, `code`.
  AbstractCode code = AbstractCode::cast(GetBytecodeArray());

  // `GetParameters` triggers a GC. (`code` becomes a dangling pointer)
  Handle<FixedArray> params = GetParameters();

  // `code` is used as a function argument. (use-after-compacting-gc bug)
  FrameSummary::JavaScriptFrameSummary summary(
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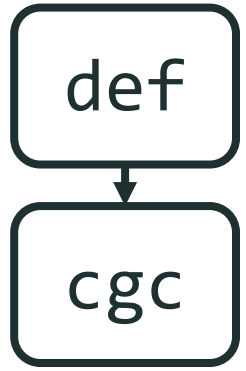

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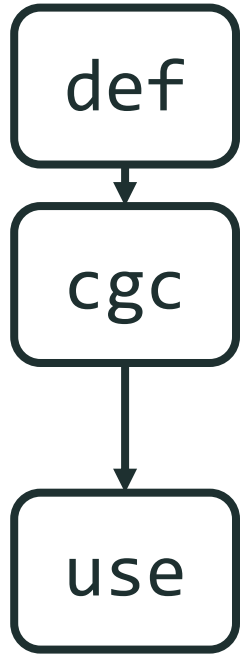
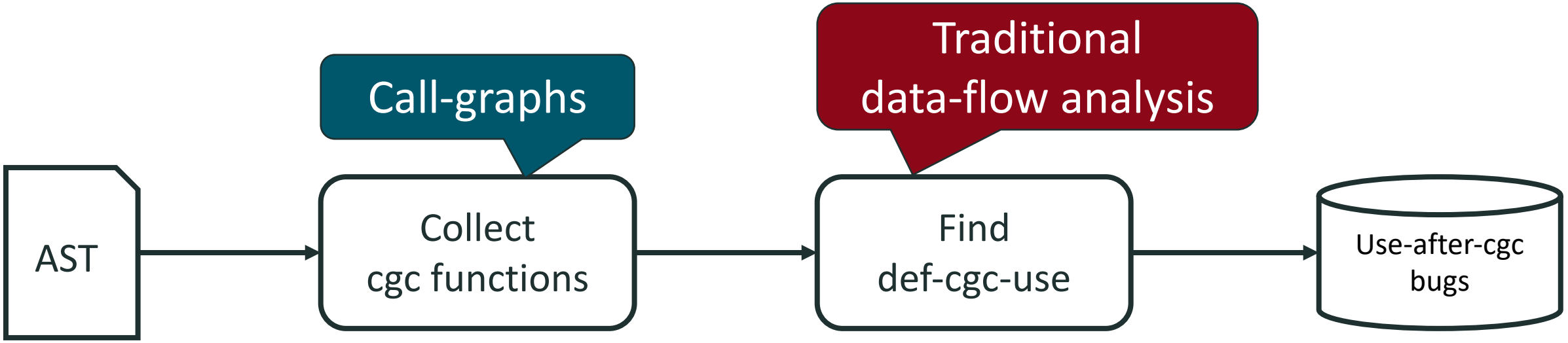


Prior Tools (gcmole, rootAnalysis)



Miss data-flow through memory

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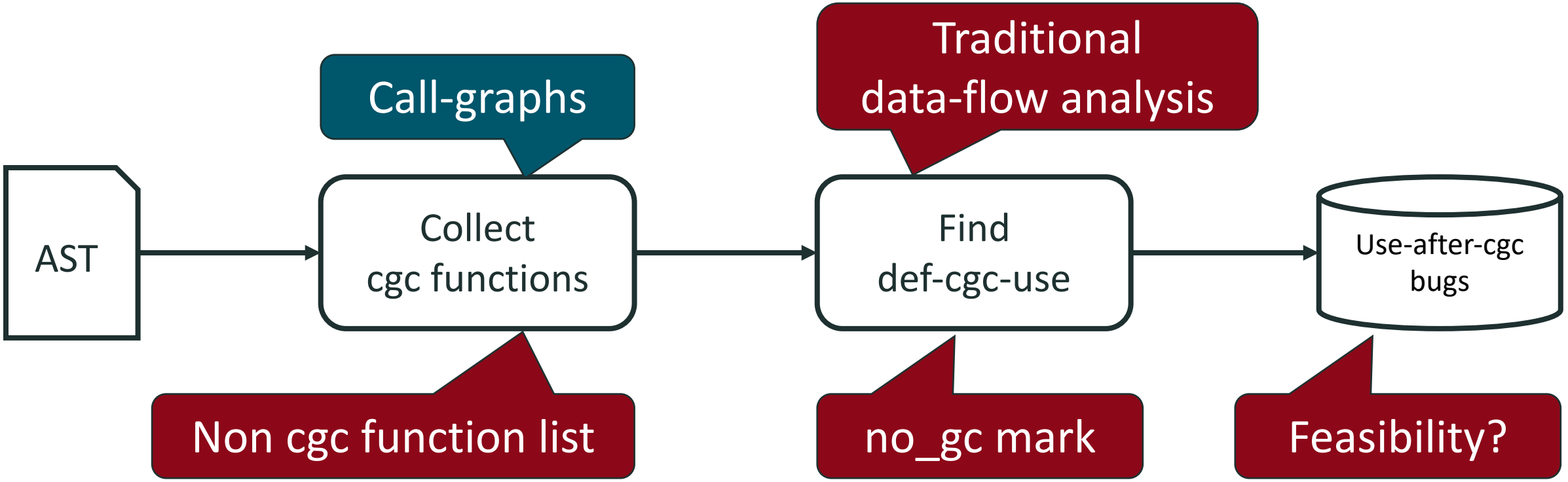

Scalable but *Path*-insensitive

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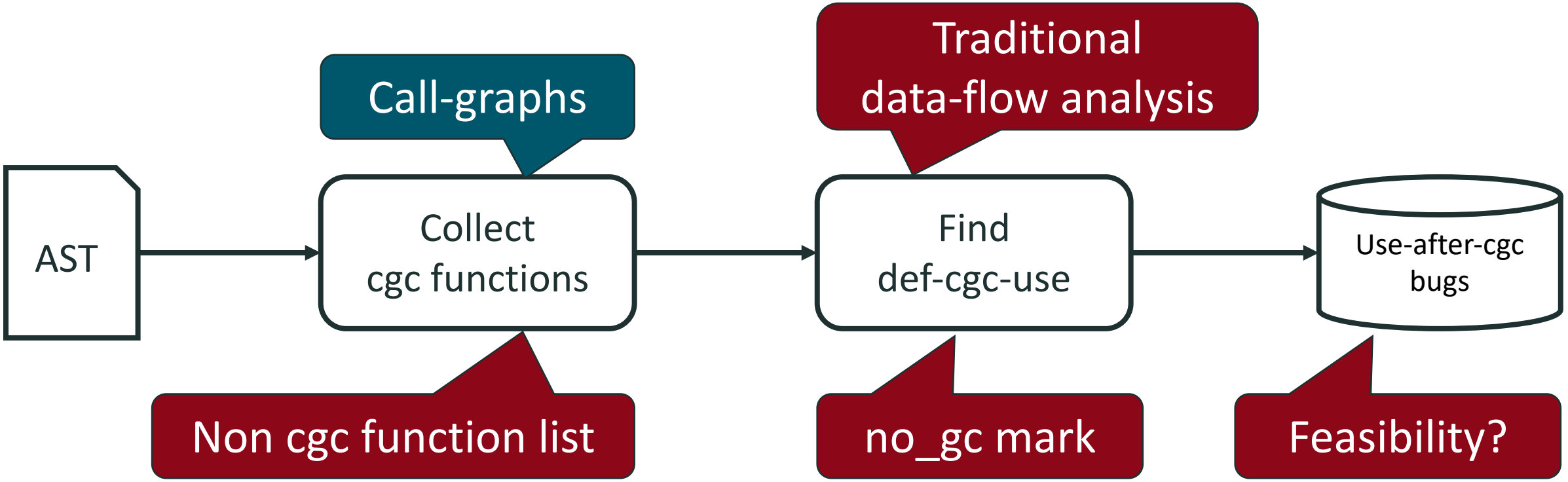


Target-specific

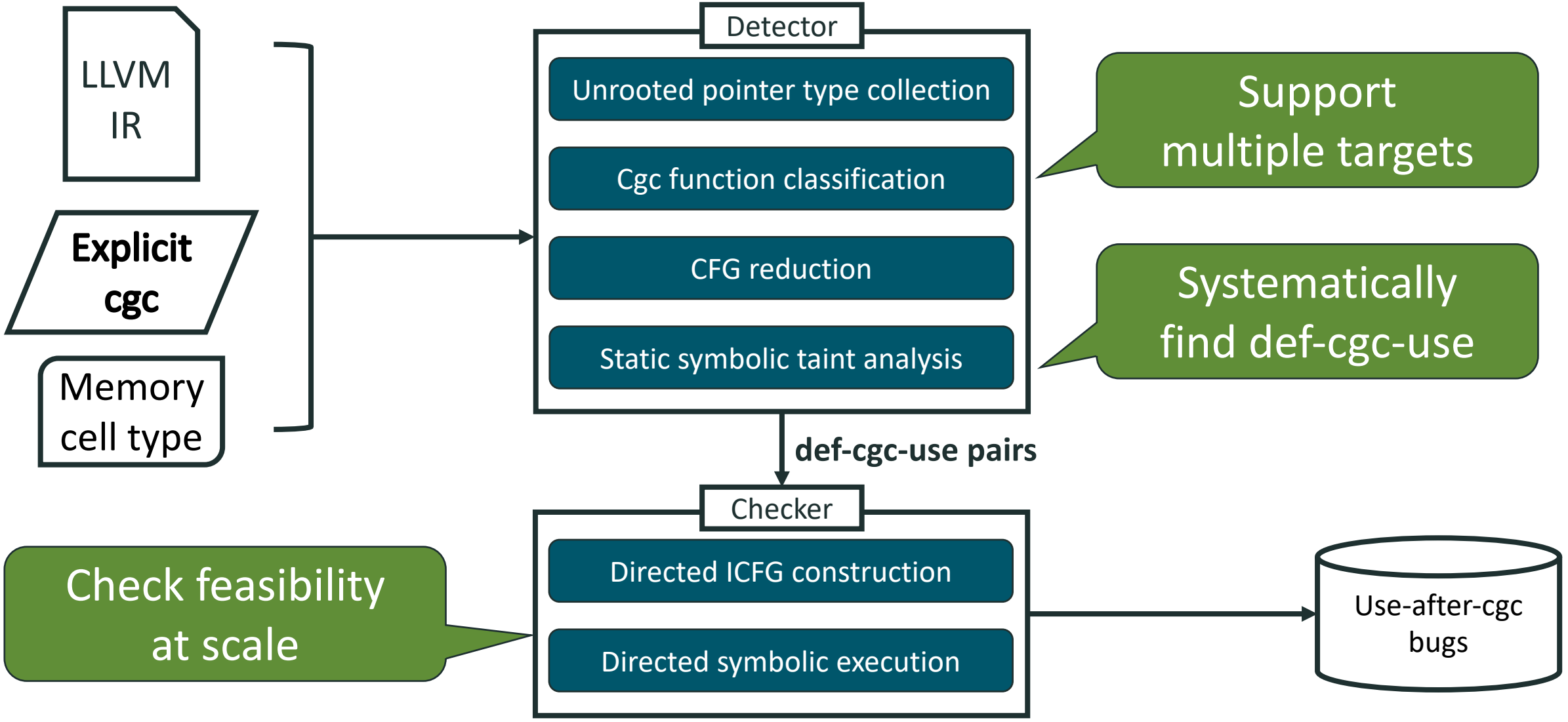
Our Goal

Support multiple targets

Systematically find def-cgc-use

Check feasibility at scale

CGSan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Memory cell type
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Unrooted pointer type collection
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CFG reduction
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Support multiple targets
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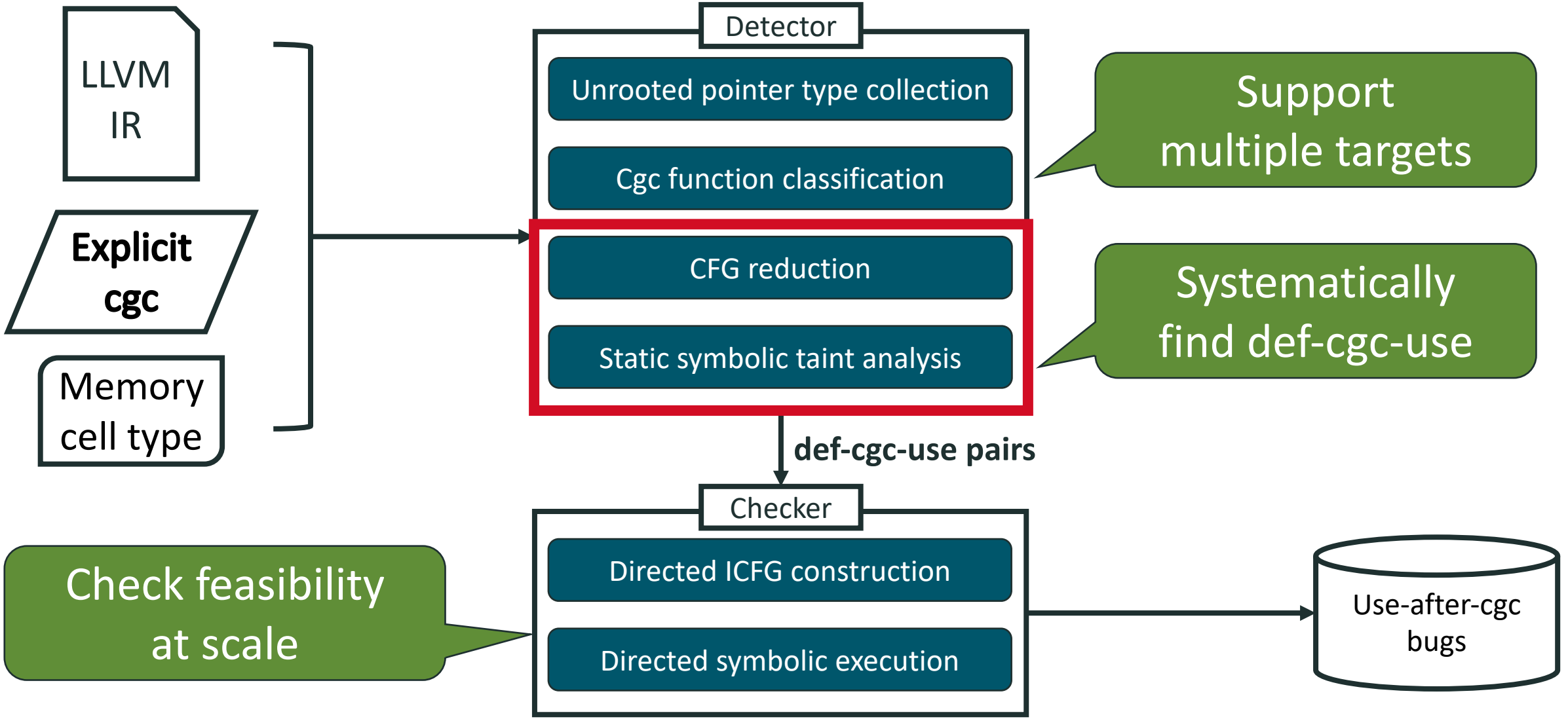
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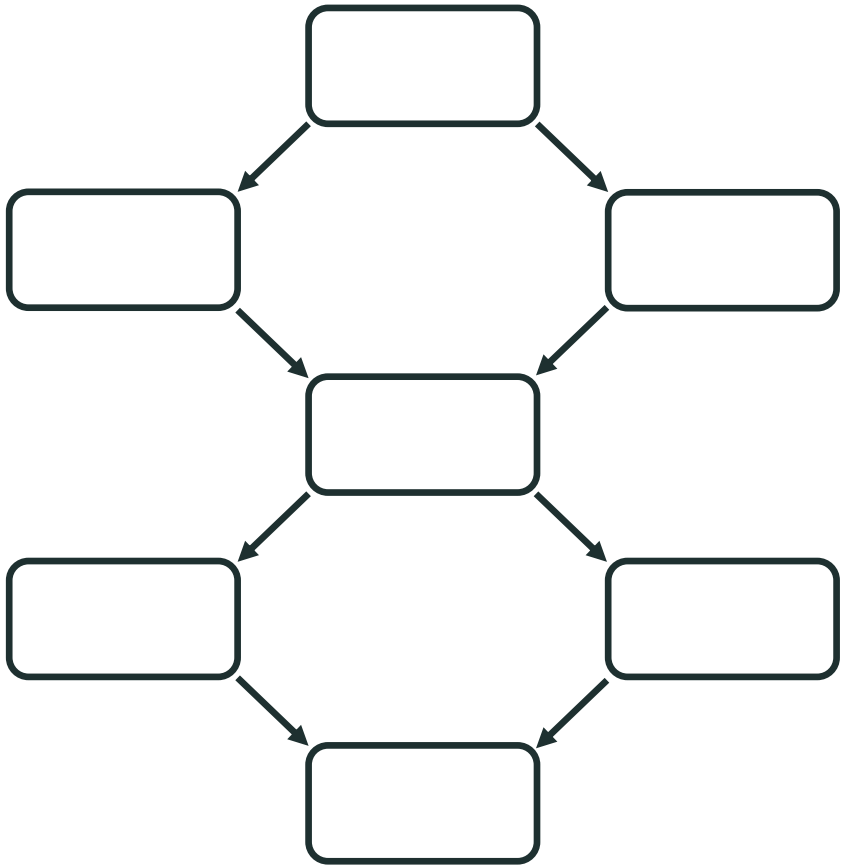
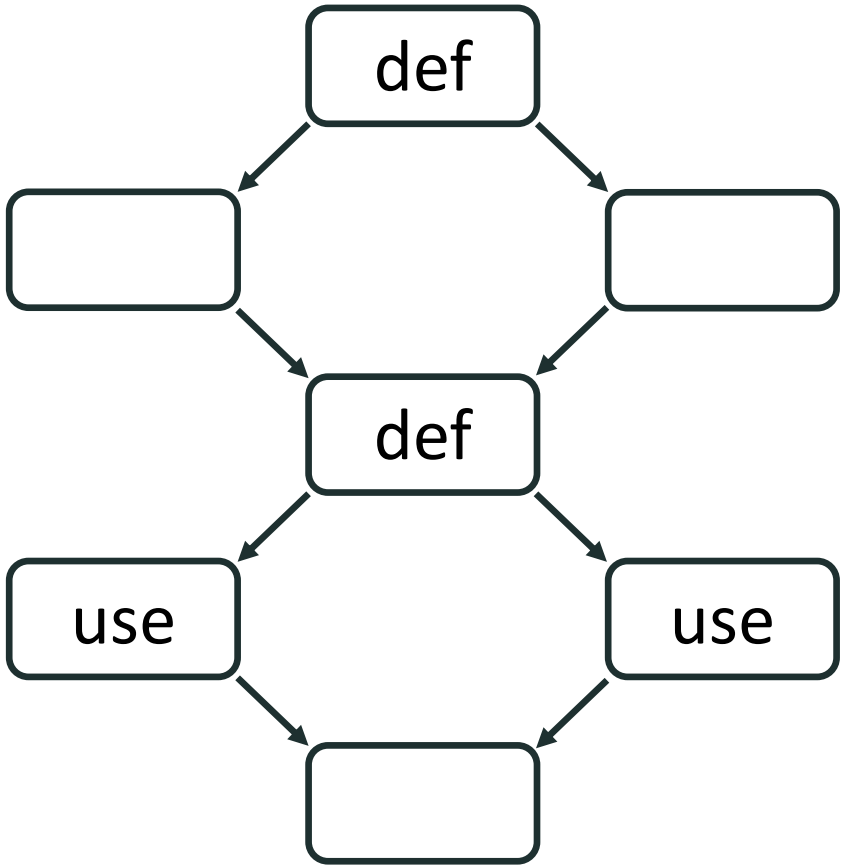
CFG Reduction

- Remove nodes and edges irrelevant to def-cgc-use.



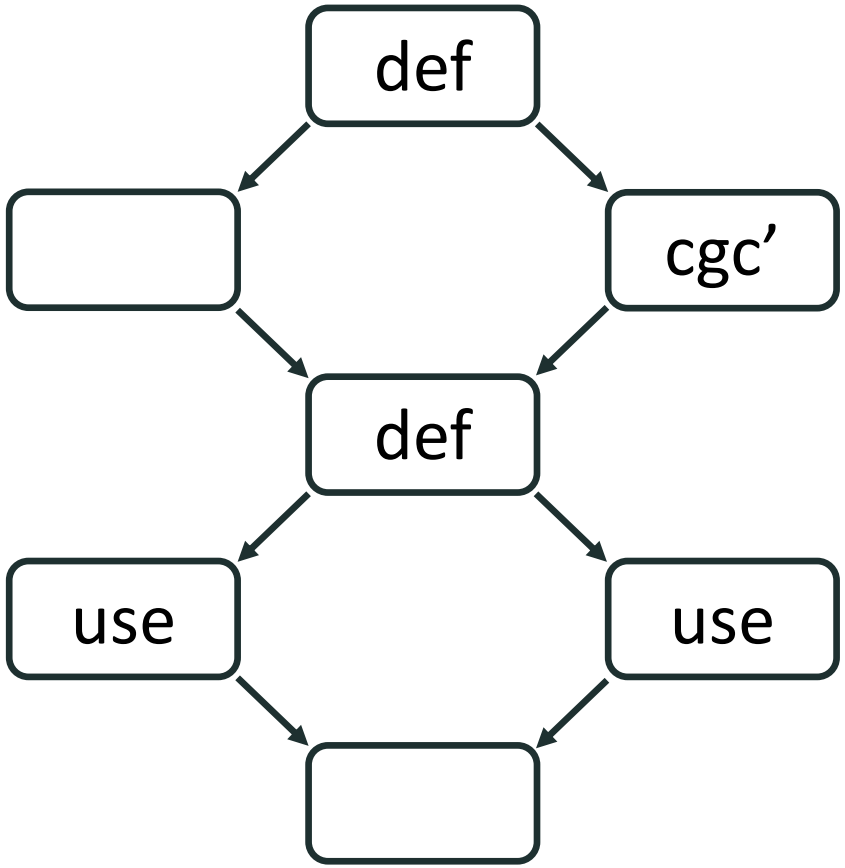
CFG Reduction

- Based on types, find nodes that define or use unrooted pointers.



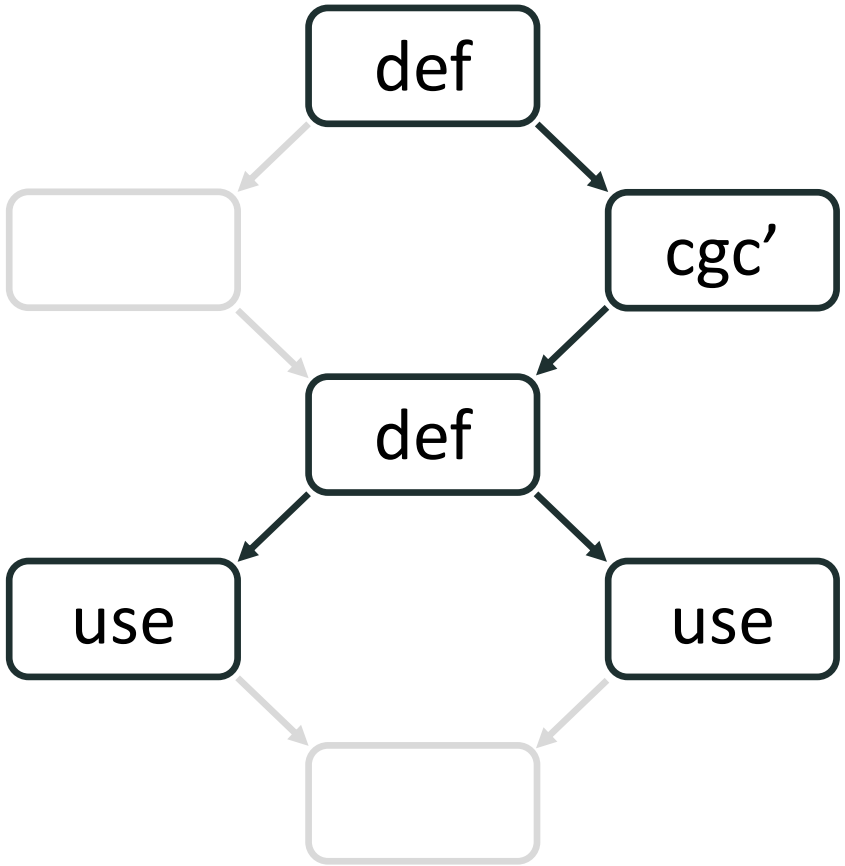
CFG Reduction

- Based on a list of cgc functions, find nodes that may trigger cgc. (Assume that cgc' internally triggers cgc.)



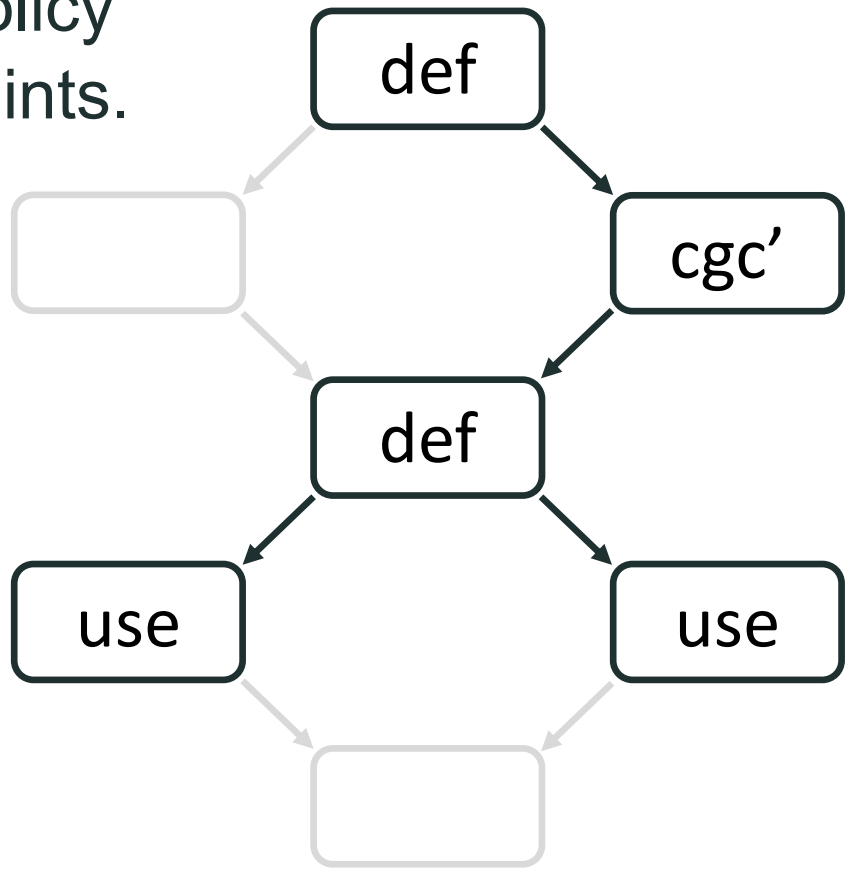
CFG Reduction

- Remove nodes and edges not in def-cgc-use paths.



Static symbolic taint analysis

- Intra-procedurally track data-flows of unrooted pointers by symbolic evaluation while following the reduced CFG.
  - Type-based taint policy
  - Ignore path constraints.



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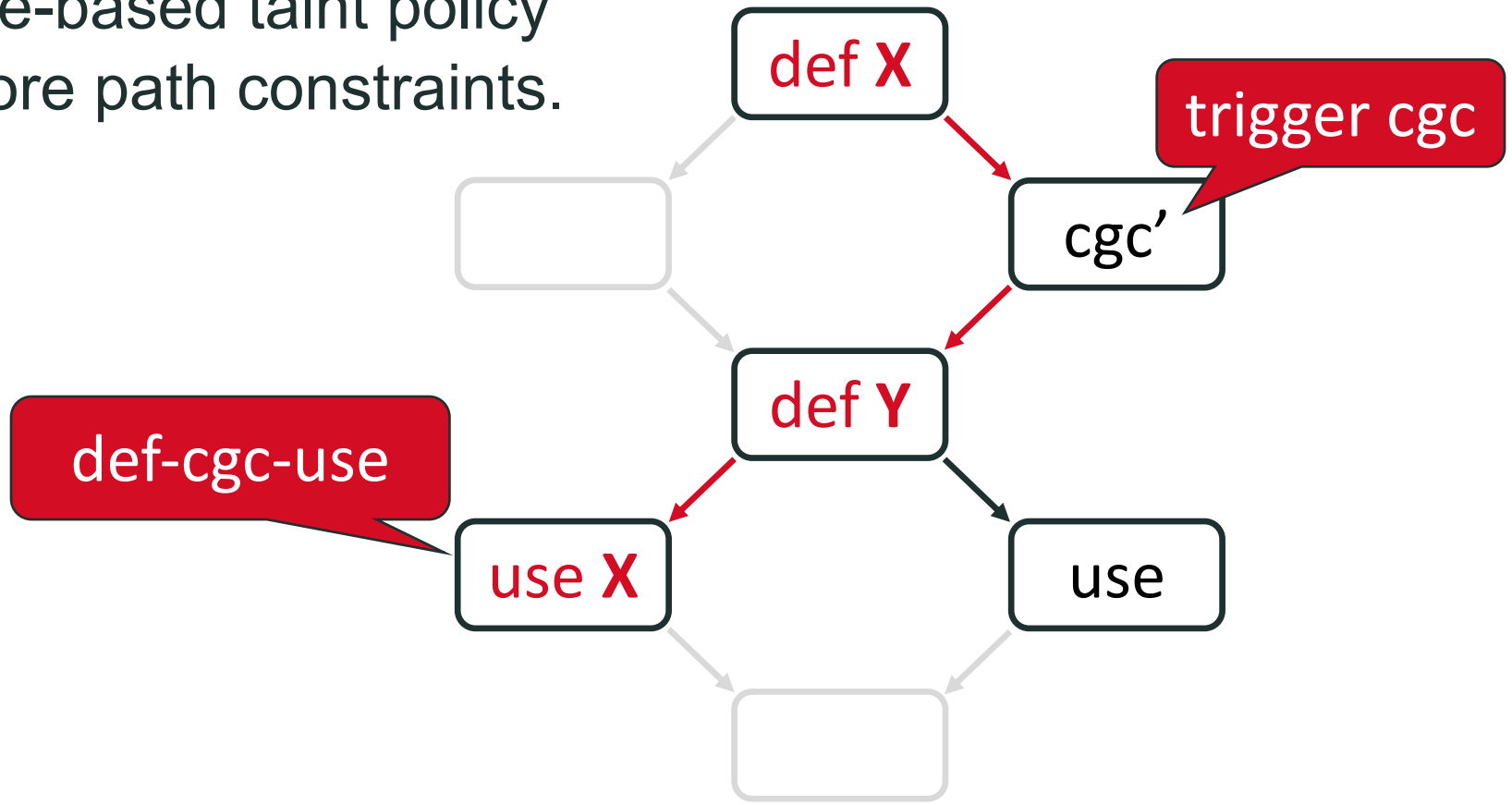

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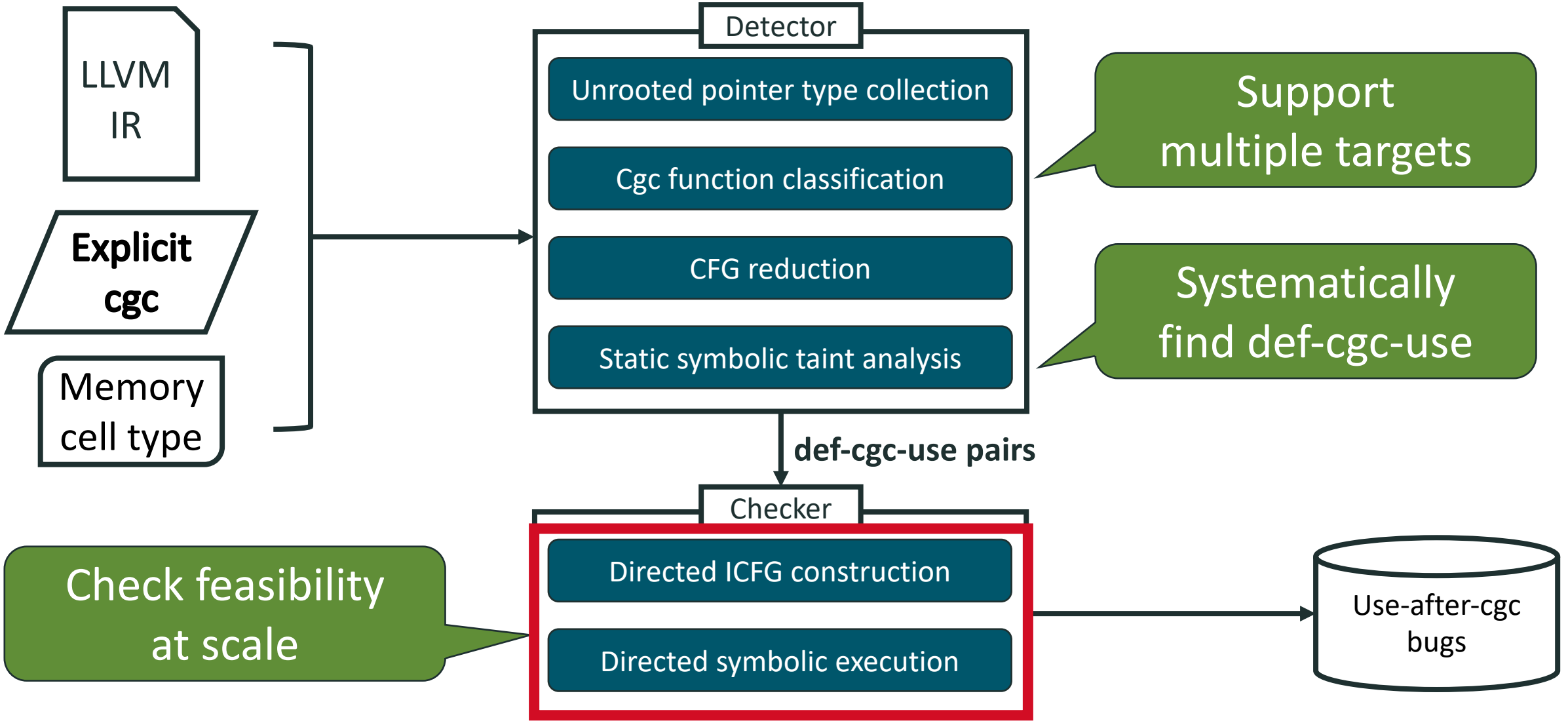
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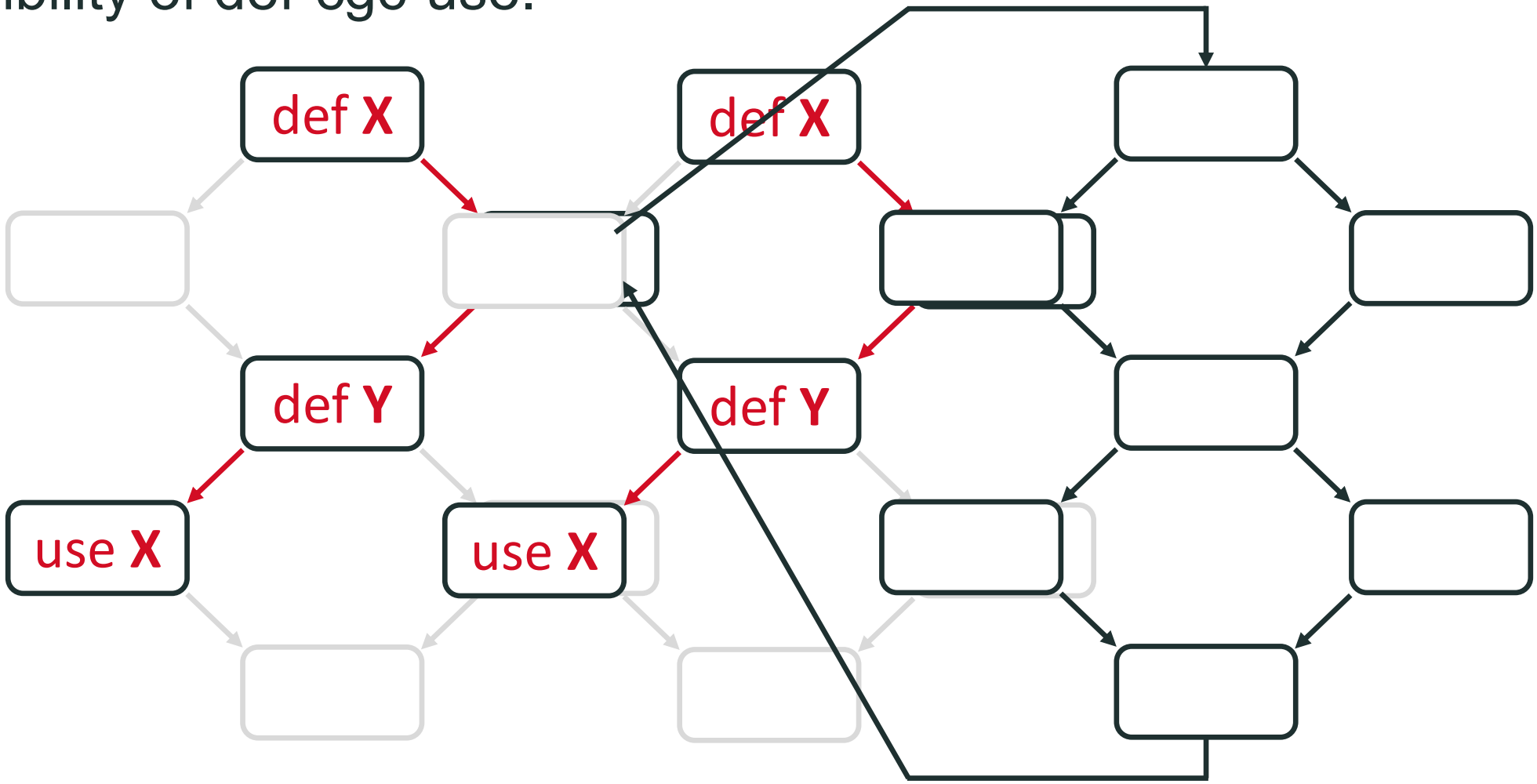
Directed ICFG Construction

- Optimize ICFG by removing nodes and edges irrelevant to checking feasibility of def-cgc-use.



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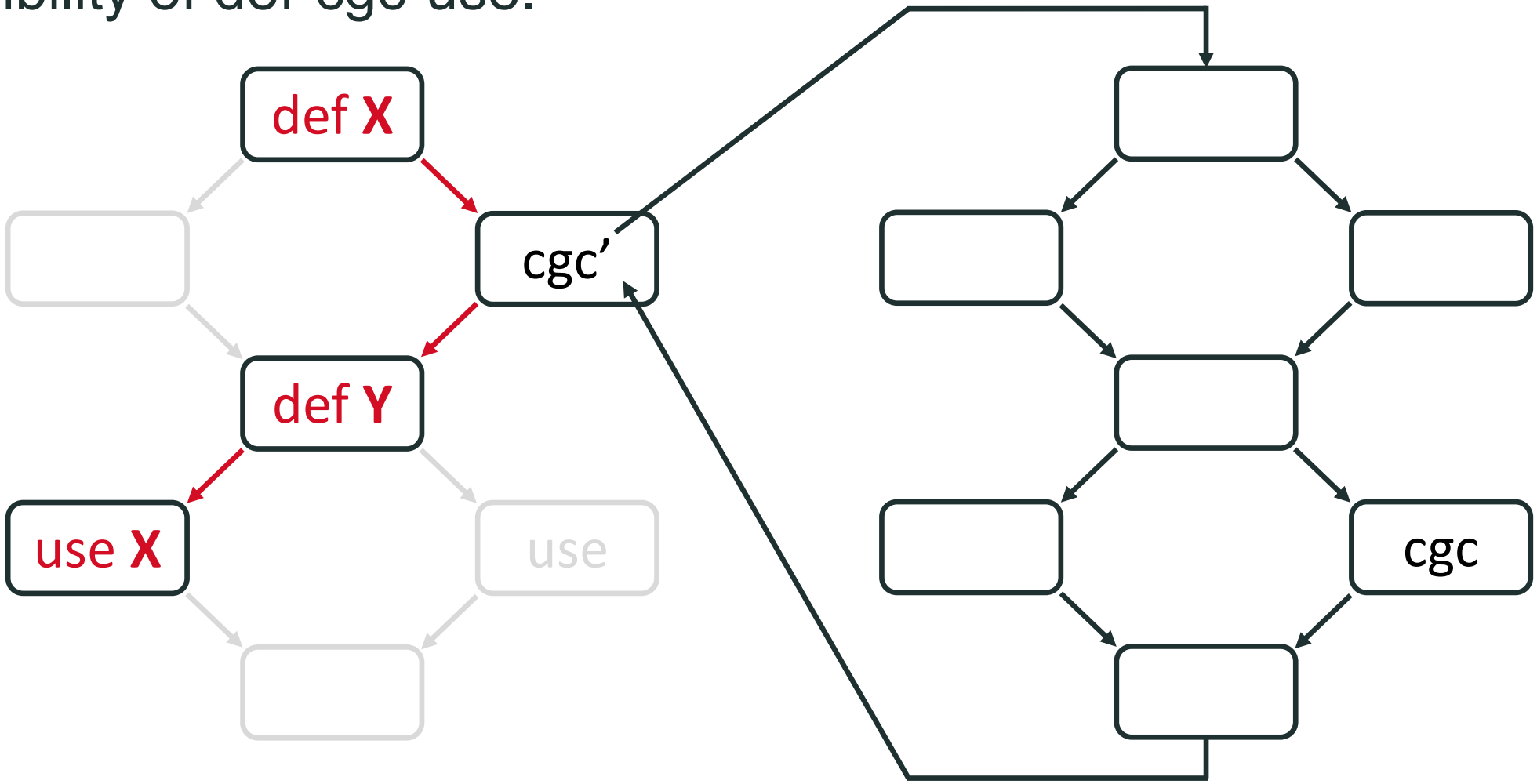

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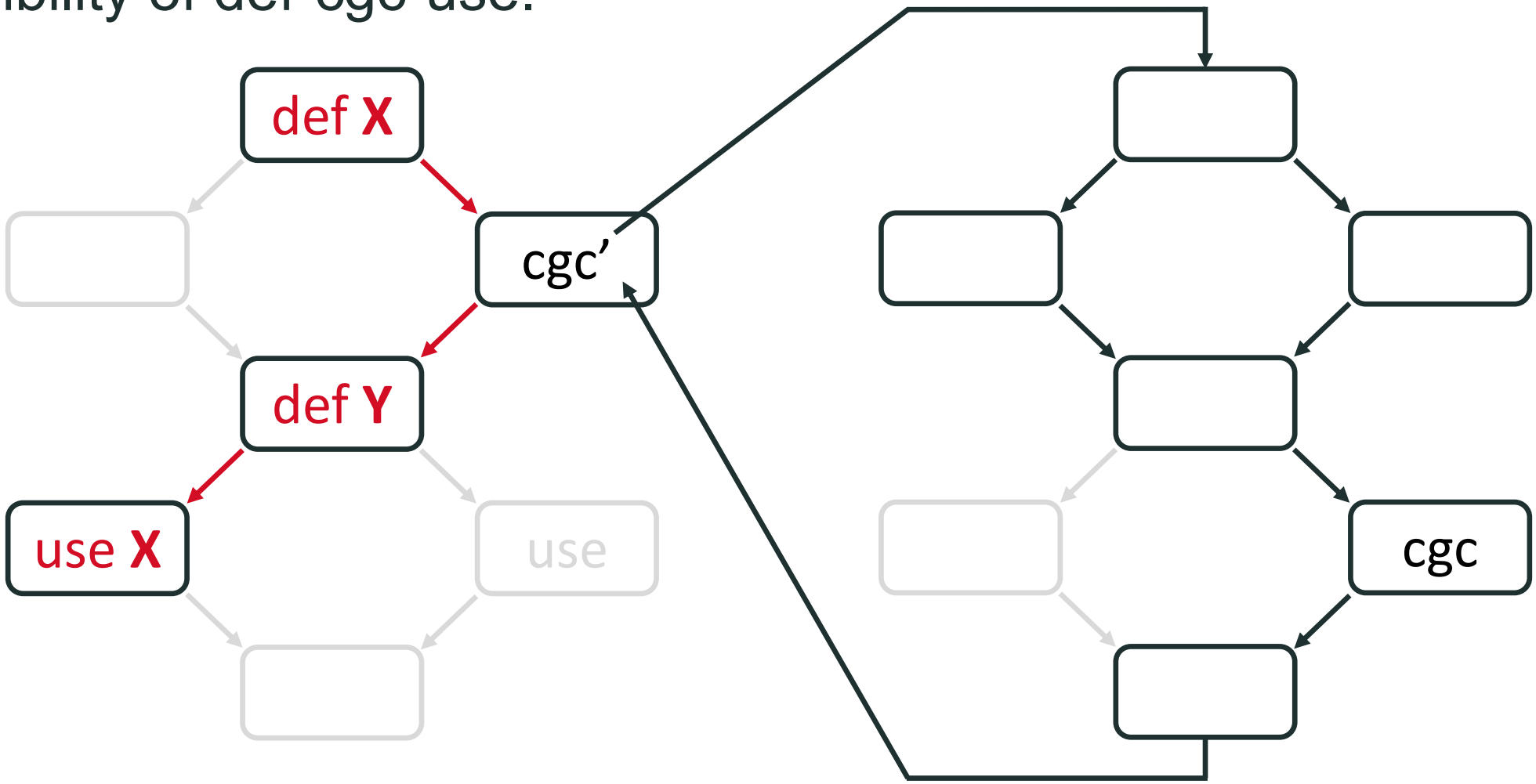

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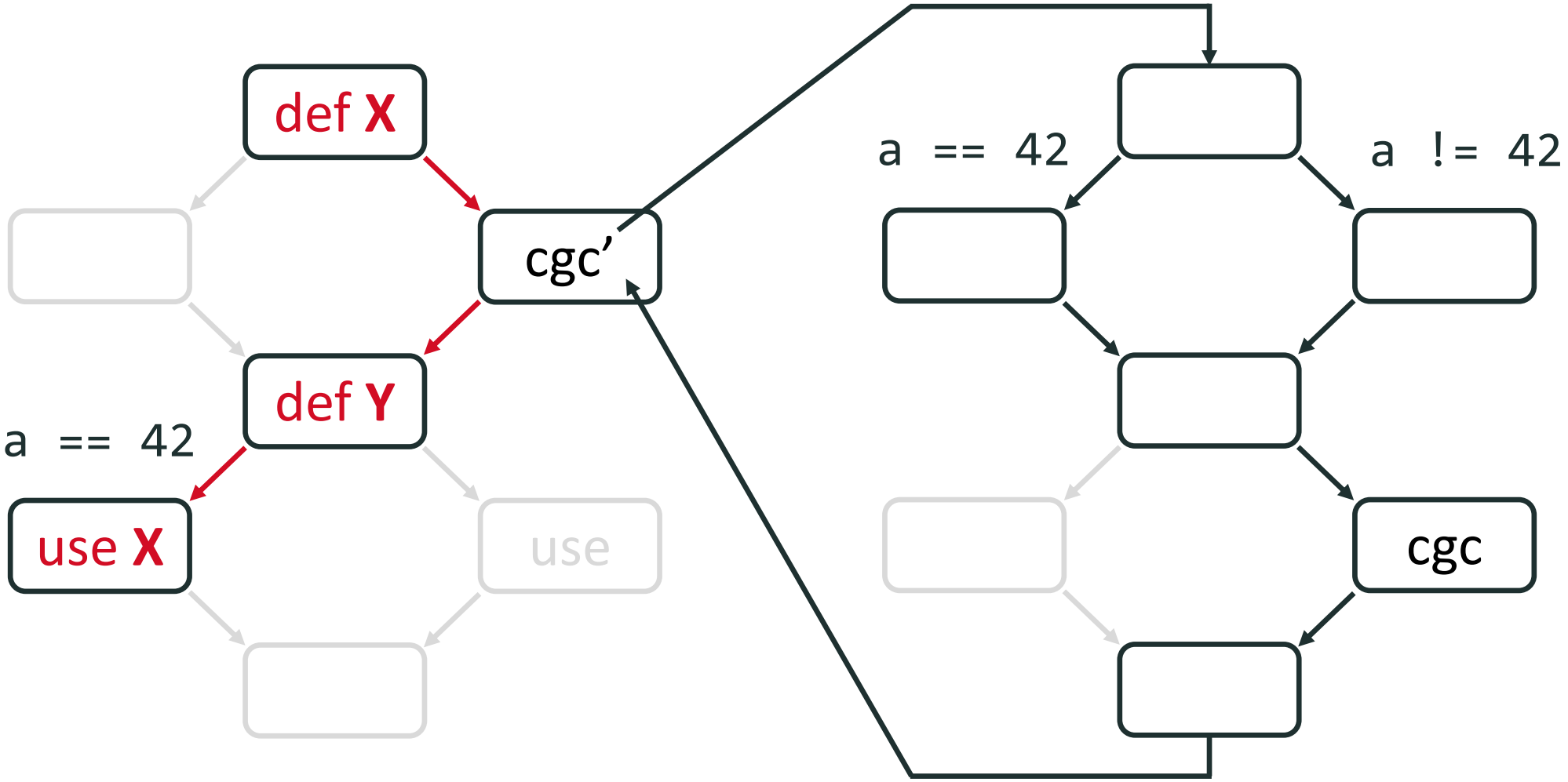

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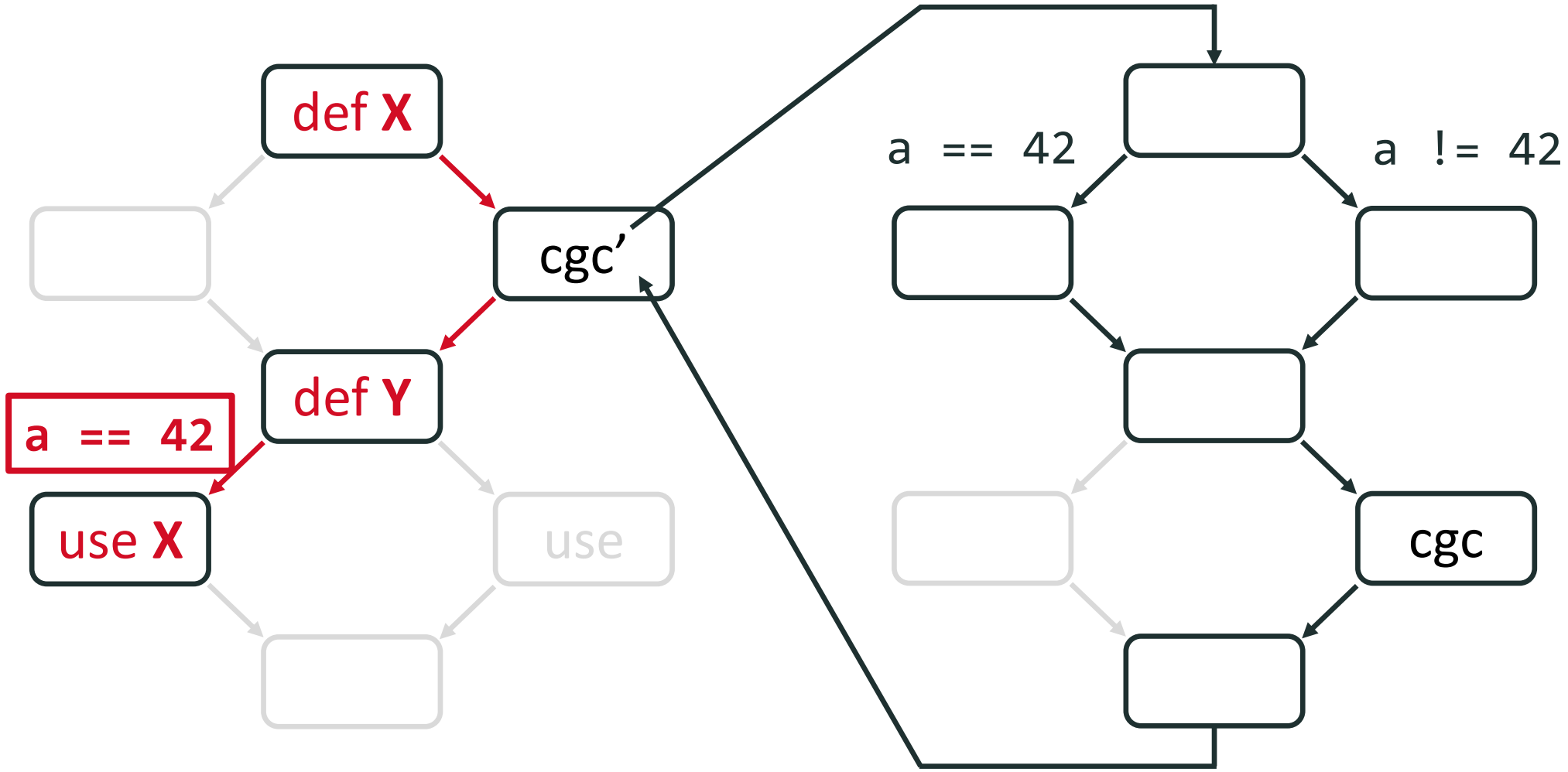

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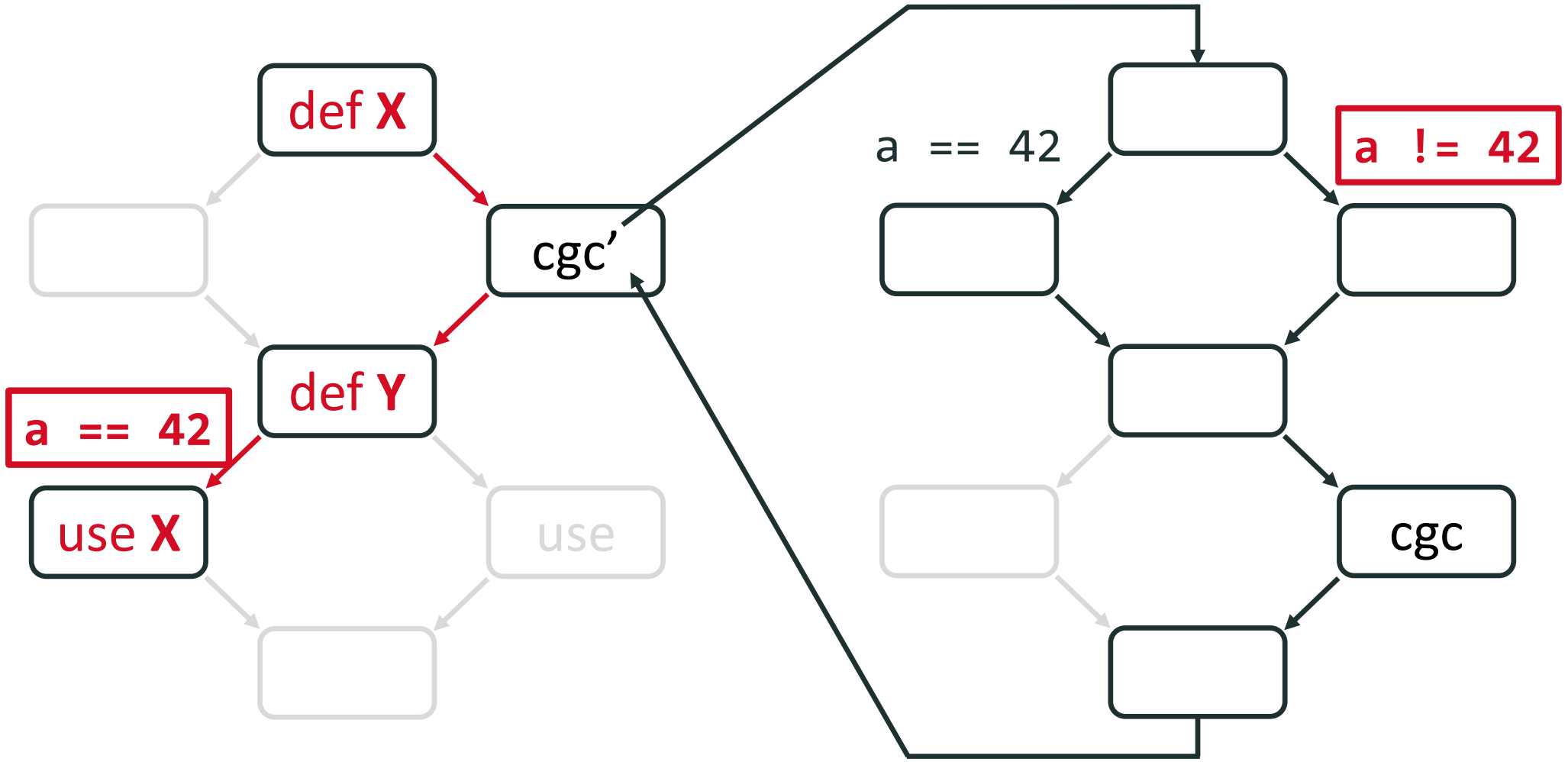

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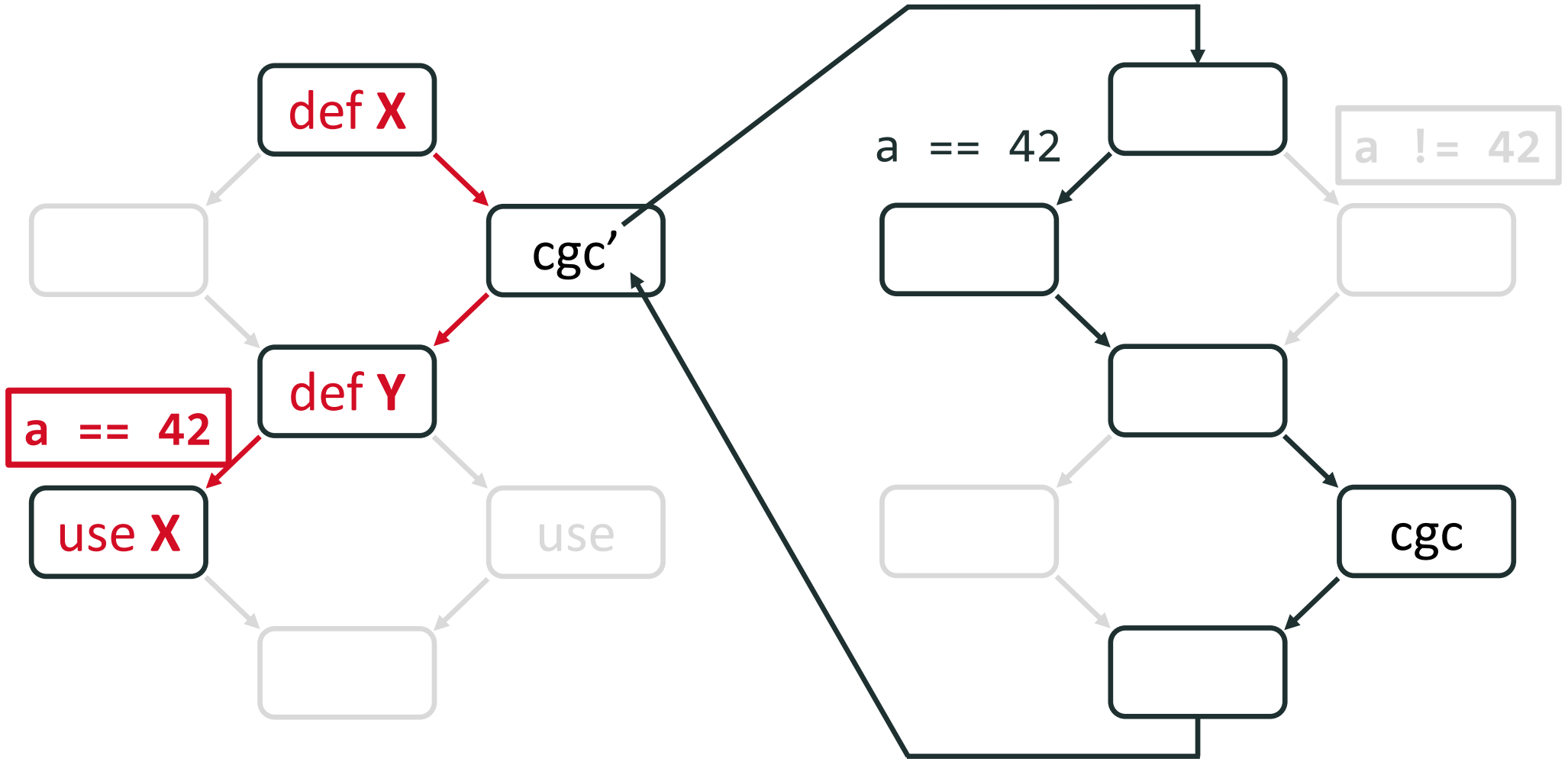
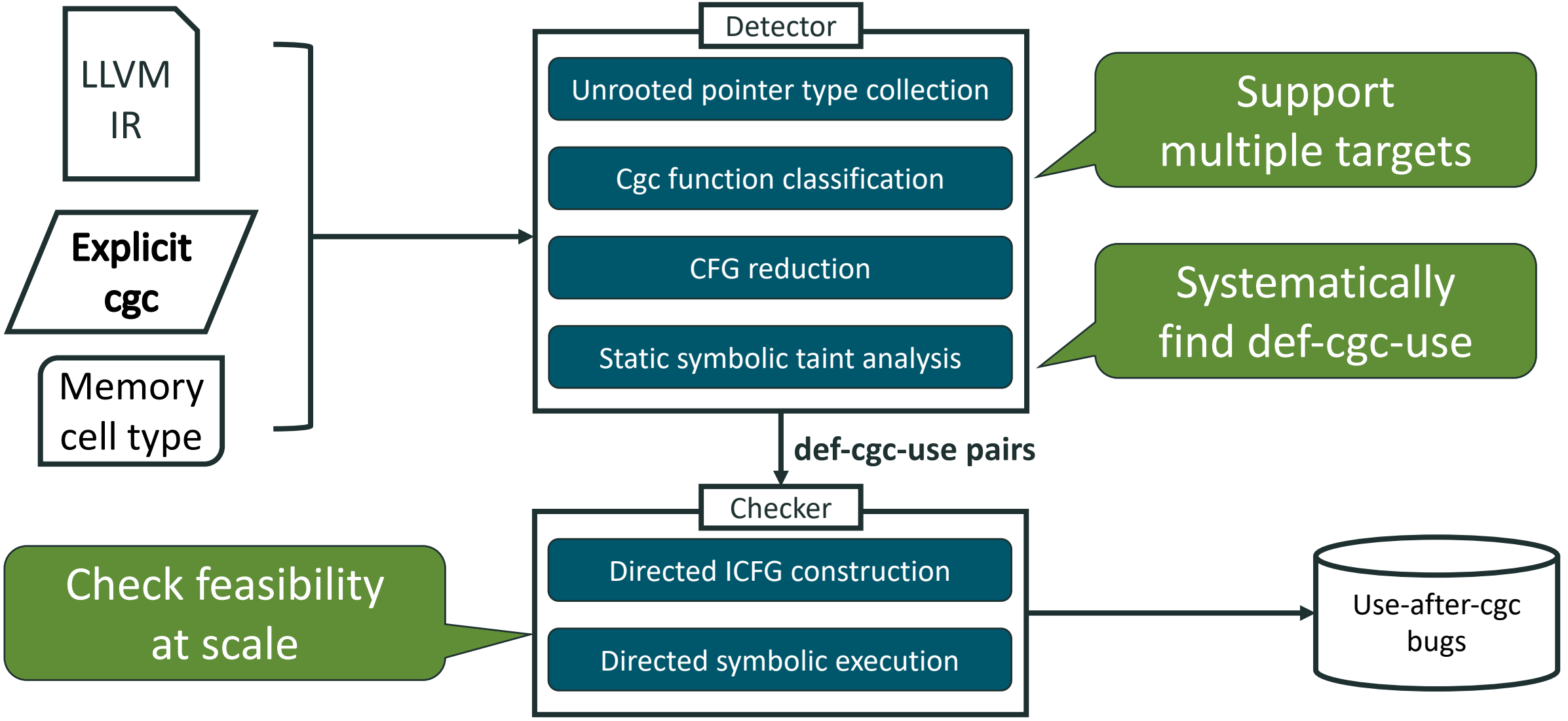


Directed Symbolic Execution

- Check feasibility of def-cgc-use while traversing the directed ICFG.
  - Inter-procedural symbolic execution
  - Under-constrained symbolic execution

- Prioritize path traversals using the directed scheduling
  - Loop scheduling
  - Stateful scheduling
  - Retrievable scheduling

Evaluation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Experiment Setup

- The latest two JavaScript engines
  - Google V8 8.1
  - Mozilla SpiderMonkey 74

- Memory cell type
  - V8: Object
  - SpiderMonkey: Cell

- Compacting GC function
  - V8: `CollectGarbage`
  - SpiderMonkey: `gc`

- Timeouts
  - 10 seconds for analyzing a function in the detector module
  - 10 minutes for checking the feasibility of a detected def-cgc-use in the checker module

Detector Statistics

- Detector totally found 1,484 def-cgc-use pairs in 71 minutes while having 230 timeout cases.

- With CFG reduction, the detection time decreased by 40% and timeout cases decreased by 48%.

Target	DETECTOR w/ CFG reduction			DETECTOR w/o CFG reduction		
	def-cgc-use	Timeout	Time	*def-cgc-use*	Timeout	Time
V8	20	112	36m	20	263	67m
SpiderMonkey	1,464	118	35m	1,426	178	51m

Checker Statistics

- Checker found 18 feasible def-cgc-use pairs and verified 1,309 infeasible def-cgc-use pairs.

- After using the directed ICFG, checker detected 2.25x feasible def-cgc-use pairs and 163x infeasible def-cgc-use pairs.
  - The average time to check a def-cgc-use pair decreased by 83%.

Target	CHECKER w/ Directed ICFG				CHECKER w/o Directed ICFG			
	Feasible	Infeasible	Timeout	Avg. Time	Feasible	Infeasible	Timeout	Avg. Time
V8	18	0	2	98s	8	0	12	364s
SpiderMonkey	0	1,309	155	64s	0	8	1,456	597s

Bug Findings

- Triage def-cgc-use pairs by their function names.

Idx	Function	Def	Use	Status	Patch Strategy	Prev.
1	BaseNameDictionary<Derived, Shape>::CollectKeysTo	Call	Call	Fixed	Relocate *compact-gc*	✗
2	Deserializer::DeserializeDeferredObjects	Call	Call	Fixed	Remove *compact-gc*	✗
3	Deserializer::ReadObject	Call	Return	Fixed	Remove *compact-gc*	✗
4	Factory::AllocateRawWithImmortalMap	Arg	Call	Won't Fix	-	✓
5	Factory::NewFixedArrayWithFiller	Arg	Call	Fixed	Use *rooted* pointer	✓
6	Logger::ICEvent	Arg	Call	Fixed	Use *rooted* pointer	✓
7	Logger::MapEvent	Arg	Call	Fixed	Use *rooted* pointer	✗
8	Map::DeprecateTransitionTree	Arg	Call	Submitted	-	✗
9	MapUpdater::ConstructNewMap	Call	Call	Fixed	Use *rooted* pointer	✓
10	NativeRegExpMacroAssembler::CheckStackGuardState	Arg	Call	Won't Fix	-	✗
11	ObjectDeserializer::Deserialize	Call	Store	Fixed	Remove *compact-gc*	✗
12	PartialDeserializer::Deserialize	Call	Call	Fixed	Remove *compact-gc*	✗
13	SourceTextModule::AddAsyncParentModule	Arg	Call	Fixed	Use *rooted* pointer	✗
14	ToPropertyDescriptorFastPath	Call	Call	Fixed	Relocate *compact-gc*	✗
15	V8HeapExplorer::AddEntry	Arg	Store	Fixed	Remove *compact-gc*	✓

Limitation

- We assume that compacting GC must move all unrooted pointers.
- We cannot handle compacting GC triggered in other threads.
- Path explosion problem still existed.

More in the paper

- Directed scheduling
- Patch strategies for use-after-cgc bugs
- Other evaluation and details

Question?