Polymorphic Type Inference for Machine Code

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Introduction

The challenge

Given an optimized, real-world binary with no debug information, recover the original source-level types of program variables in the binary.

What is it good for?

- Reverse-engineering and program understanding.
- Better decompilation [Schwartz et al., 2013]
- Narrowing the focus of further analysis passes.

Why is type reconstruction difficult?

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Challenges

- Accurate disassembly is hard!
- C and C++ have unsound type systems.
- Programmers introduce ad-hoc type disciplines.
- Polymorphic functions exist!
- Compiler optimizations can be performed on type-erased code.

Examples

```
;; disassemble...
call foo
;; ...now keep going?
```

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Examples

- Bit-twiddling
- Untagged unions and type-punning
- Quake III inverse sqrt
- Stealing unused pointer bits
- Downcasts (from generic to specific)
- xor-combined doubly-linked lists

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Examples

- `typedef` aliases (`HANDLE`, `size_t`)
- Basic types with specific purposes (file descriptors, IP addresses)
- Entire un-enforced type hierarchies! (`HBRUSH` *extends* `HGDI`)

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Examples

- Nominal subtype polymorphism
- Physical subtype polymorphism
  `struct { FILE* x; char* y; }`
  extends `FILE*`
- Emulated polytypes (allocators, `memcpy`)

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Examples

```c
T * get_T(void)
{
  S * s = get_S();
  if (s == NULL) {
    return NULL;
  }
  T * t = S2T(s);
  return t;
}
```

```
get_T:
    call get_S
    test eax, eax
    jz   local_exit
    push eax
    call S2T
    add  esp, 4
local_exit:
    ret
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Returns (T*) NULL

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Returns `(T*) NULL`

Returns `(S*) NULL`!

Type system desiderata

Based on a survey of idioms found in optimized C and C++ binaries, we need

- Subtypes (nominal and physical)
- Polymorphic functions
- Recursive types

and a reconstruction algorithm that is

- Scalable
- Not unification-driven
- Does not require much sound points-to data

Static approaches to type reconstruction

	TIE	SecondWrite	Theory Prop.	Retypd
Appeared in	NDSS '11	PLDI '13	PPDP '13	PLDI '16
Allows subtypes?	Limited	No	No	Yes
Points-to oracle?	Yes (DVSA)	Best-effort pts-to	via SMT	Stack only
Recursive types?	Indirect	Indirect	Yes	Yes
Polymorphic types?	No	No	No	Yes
Type system	C-like lattice	C-like lattice	Rational trees	Decorated trees
Concept	Intervals	Unsound pts-to	SMT	Pushdown automata

- Lee et al. [2011]: infer types by tracking lattice constraints.
- ElWazeer et al. [2013]: sound points-to analysis may not be required.
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The constraint system

From a program to a constraint set

- Abstract location X $\rightsquigarrow$ basic type variable x.
- Dataflow between abstract locations $\rightsquigarrow$ subtype constraints:

`mov eax,ebx` $\rightsquigarrow$ $ebx_p \sqsubseteq eax_q$

- Observed capabilities of a type variable are encoded with field labels:

`mov eax,[ebx]` $\rightsquigarrow$ $ebx_p.\mathsf{load}.@0 \sqsubseteq eax_q$

- ...even for function types!

`X = F(Y)` $\rightsquigarrow$ $f.\mathsf{out}_{\mathsf{eax}} \sqsubseteq x, \quad y \sqsubseteq f.\mathsf{in}_{\mathsf{stack0}}$

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Derived typing judgements

In addition to standard judgements for subtype relations, we would like to infer constraints between derived type variables.

$$x \sqsubseteq y, \quad x.\text{@4 exists}, \quad y.\text{@4 exists} \quad \vdash \quad x.\text{@4} \sqsubseteq y.\text{@4}$$

Caveat: Some of the capabilities must act contravariantly!

Mutable references, $x \sqsubseteq y$:

$$x.\text{load} \sqsubseteq y.\text{load}$$
$$y.\text{store} \sqsubseteq x.\text{store}$$

Functions, $f \sqsubseteq g$:

$$f.\text{out}_{\text{eax}} \sqsubseteq g.\text{out}_{\text{eax}}$$
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Constraint entailment rules

$$\frac{\alpha \sqsubseteq \beta}{\alpha \text{ exists}} \text{(T-Left)} \qquad \frac{\alpha \sqsubseteq \beta}{\beta \text{ exists}} \text{(T-Right)} \qquad \frac{\alpha \text{ exists}}{\alpha \sqsubseteq \alpha} \text{(S-Refl)} \qquad \frac{\alpha \sqsubseteq \beta, \quad \beta \sqsubseteq \gamma}{\alpha \sqsubseteq \gamma} \text{(S-Trans)}$$

$$\frac{\alpha \sqsubseteq \beta, \quad \alpha.\ell \text{ exists}}{\beta.\ell \text{ exists}} \text{(T-InheritL)} \qquad \frac{\alpha \sqsubseteq \beta, \quad \beta.\ell \text{ exists}}{\alpha.\ell \text{ exists}} \text{(T-InheritR)} \qquad \frac{\alpha.\ell \text{ exists}}{\alpha \text{ exists}} \text{(T-Prefix)}$$

$$\frac{\alpha \sqsubseteq \beta, \quad \beta.\ell \text{ exists}, \quad \ell \text{ covariant}}{\alpha.\ell \sqsubseteq \beta.\ell} \text{(S-Field}_{\oplus}\text{)} \qquad \frac{\alpha \sqsubseteq \beta, \quad \beta.\ell \text{ exists}, \quad \ell \text{ contravariant}}{\beta.\ell \sqsubseteq \alpha.\ell} \text{(S-Field}_{\ominus}\text{)}$$

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Who needs points-to analysis?

Challenge: Prove $X \sqsubseteq Y$ for the program

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 q := p;
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: $\left\{ \begin{array}{c} P \sqsubseteq Q \\ X \sqsubseteq Q.\mathsf{store.@0} \\ P.\mathsf{load.@0} \sqsubseteq Y \end{array} \right\}$

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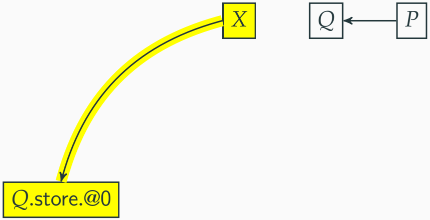

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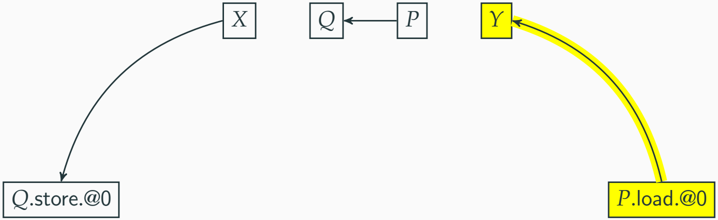

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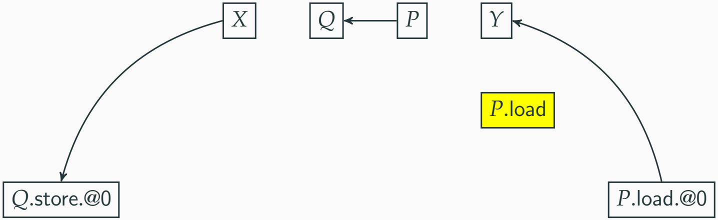

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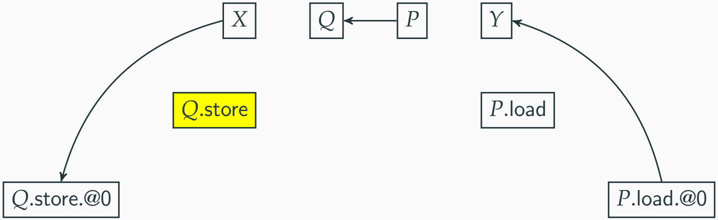

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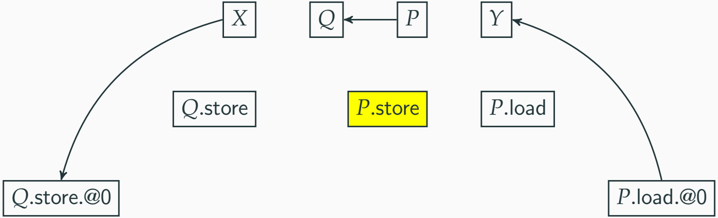

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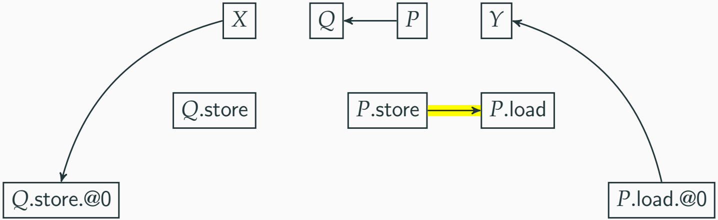

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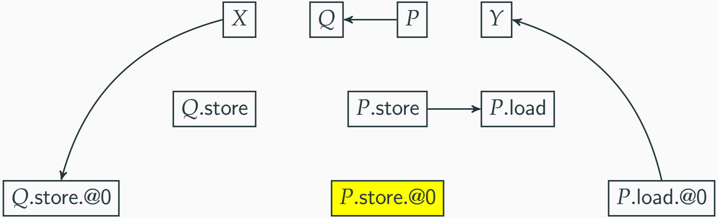
: $\left\{ \begin{array}{c} P \sqsubseteq Q \\ X \sqsubseteq Q.\mathsf{store}.@0 \\ P.\mathsf{load}.@0 \sqsubseteq Y \end{array} \right\}$

Idea: Model entailment with graph reachability?



$$\frac{P.\mathsf{store} \sqsubseteq P.\mathsf{load}, \quad P.\mathsf{load}.@0 \text{ exists}}{P.\mathsf{load}.@0 \text{ exists}} \text{(T-InheritR)}$$

Who needs points-to analysis?

Challenge: Prove $X \sqsubseteq Y$ for the program

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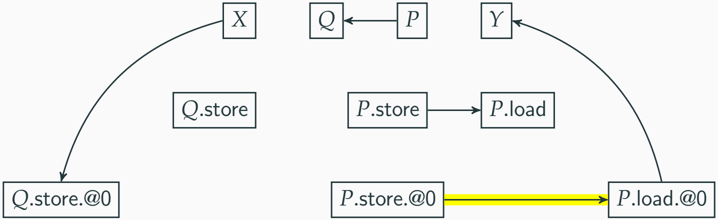

$$\frac{P.\mathsf{store} \sqsubseteq P.\mathsf{load},\quad P.\mathsf{load}.@0 \text{ exists},\quad @0 \text{ covariant}}{P.\mathsf{store}.@0 \sqsubseteq P.\mathsf{load}.@0}\ (\text{S-Field}_{\oplus})$$

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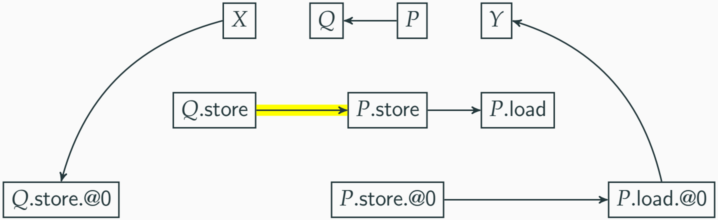

$$\frac{P \sqsubseteq Q, \qquad Q.\mathsf{store}\ \text{exists}, \qquad \mathsf{store}\ \text{contravariant}}{Q.\mathsf{store} \sqsubseteq P.\mathsf{store}}\ (\text{S-Field}_{\ominus})$$

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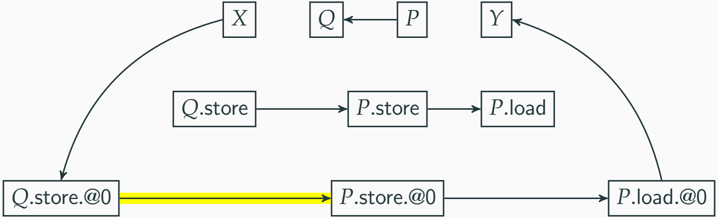

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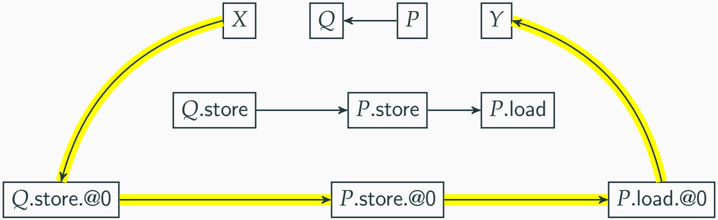

What about recursive constraints?

The problem with recursive constraints

One constraint entailed infinitely many; no finite graph suffices.

$$\{X \sqsubseteq X.\mathsf{load}.@0\}$$

$$\boxed{X} \longrightarrow \boxed{X.\mathsf{load}.@0}$$

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Taming the infinite

Abstracting the tails

What went wrong in the recursive example?

One constraint, infinitely many edges:

$$\boxed{X.w} \longrightarrow \boxed{Y.w} \quad \text{or} \quad \boxed{X.w} \longleftarrow \boxed{Y.w}$$

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Solution: Abstract away the tails

Collapse all of these edges into just two!

$$\boxed{X.\oplus} \longrightarrow \boxed{Y.\oplus} \qquad \boxed{X.\ominus} \longleftarrow \boxed{Y.\ominus}$$

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$$\{X.w \mid \mathcal{C} \vdash X.w \text{ exists} \wedge w \text{ covariant seq.}\}$$

Labeled edges in the finite graph

$$\mathcal{C} = \{X \sqsubseteq X.\mathsf{load}.\mathsf{@0}\}$$

$$\boxed{X.\oplus} \longrightarrow \boxed{X.\mathsf{load}.\mathsf{@0}.\oplus} \qquad \boxed{X.\ominus} \longleftarrow \boxed{X.\mathsf{load}.\mathsf{@0}.\ominus}$$

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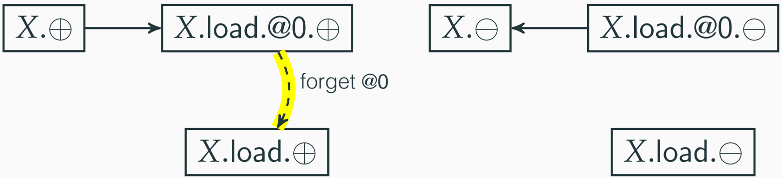

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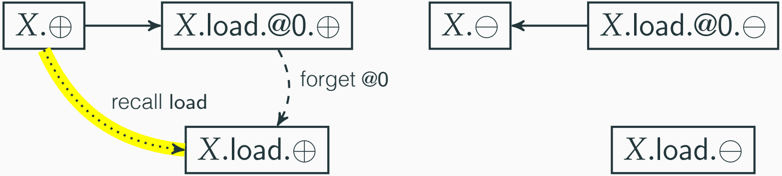

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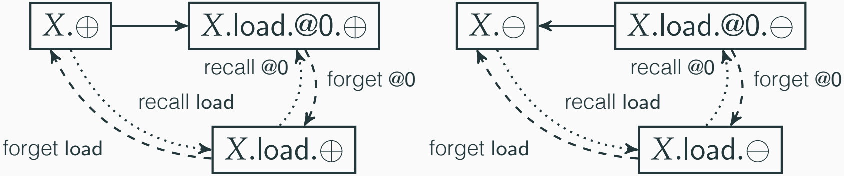

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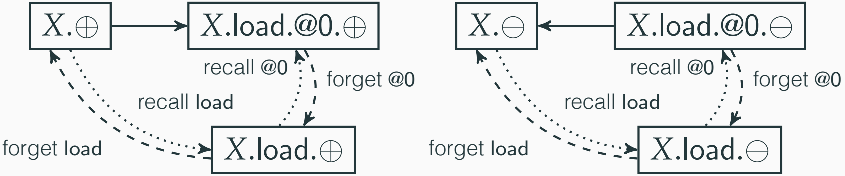

$$\mathsf{forget}\ \alpha \cdot \mathsf{recall}\ \alpha = 1$$

$$\mathsf{forget}\ \alpha \cdot \mathsf{recall}\ \beta = 0$$

What can you get from manipulating constraints as graphs?

- Automata that recognize the entailment closure $\overline{\mathcal{C}} = \{c \mid \mathcal{C} \vdash c\}$
- Simplified / minimized constraint sets for type schemes.
- Satisfiability checks.
- Construction of sketches (marked regular trees) satisfiying the constraints.

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Example: A recursive type in the wild

```c
#include <stdlib.h>

struct LL
{
    struct LL * next;
    int handle;
};

int close_last(struct LL * list)
{
    while (list->next != NULL)
    {
        list = list->next;
    }
    return close(list->handle);
}
```

```asm
close_last:
    push    ebp
    mov     ebp,esp
    sub     esp,8
    mov     edx,dword [ebp+arg_0]
    jmp     loc_8048402
loc_8048400:
    mov     edx,eax
loc_8048402:
    mov     eax,dword [edx]
    test    eax,eax
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    mov     eax,dword [edx+4]
    mov     dword [ebp+arg_0],eax
    leave
    jmp     __thunk_.close
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Example: A recursive type in the wild

$$F.\mathsf{in}_{\mathsf{stack0}} \sqsubseteq \delta$$
$$\alpha \sqsubseteq \varphi$$
$$\delta \sqsubseteq \varphi$$
$$\varphi.\mathsf{load}.@0 \sqsubseteq \alpha$$
$$\varphi.\mathsf{load}.@4 \sqsubseteq \alpha'$$
$$\alpha' \sqsubseteq \mathsf{close}.\mathsf{in}_{\mathsf{stack0}}$$
$$\mathsf{close}.\mathsf{out}_{\mathsf{eax}} \sqsubseteq F.\mathsf{out}_{\mathsf{eax}}$$
$$\mathsf{close}.\mathsf{in}_{\mathsf{stack0}} \sqsubseteq {}^{\#}\mathsf{FileDescriptor}$$
$${}^{\#}\mathsf{SuccessZ} \sqsubseteq \mathsf{close}.\mathsf{out}_{\mathsf{eax}}$$

```
close_last:
    push    ebp
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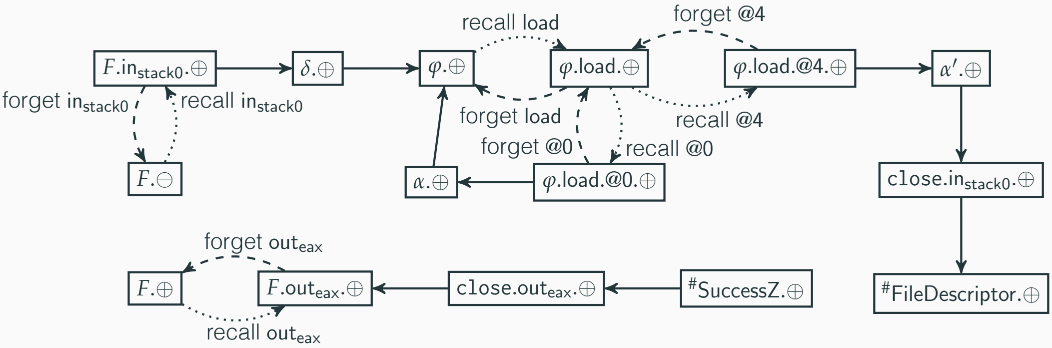
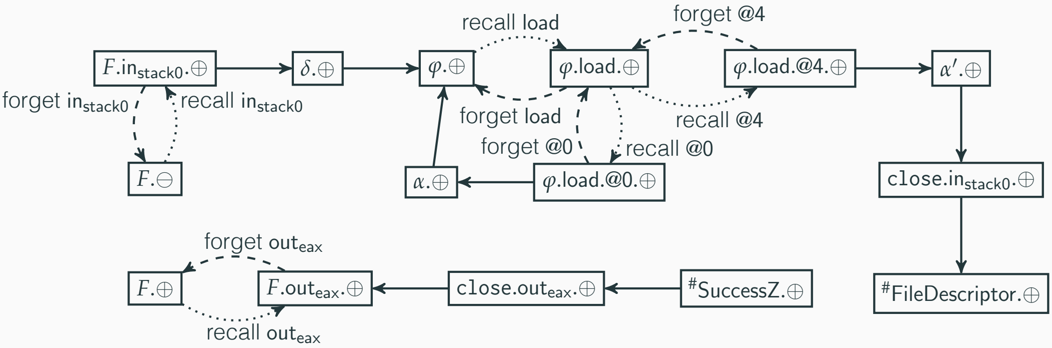
```

Example, cont'd: Simplifying constraint sets



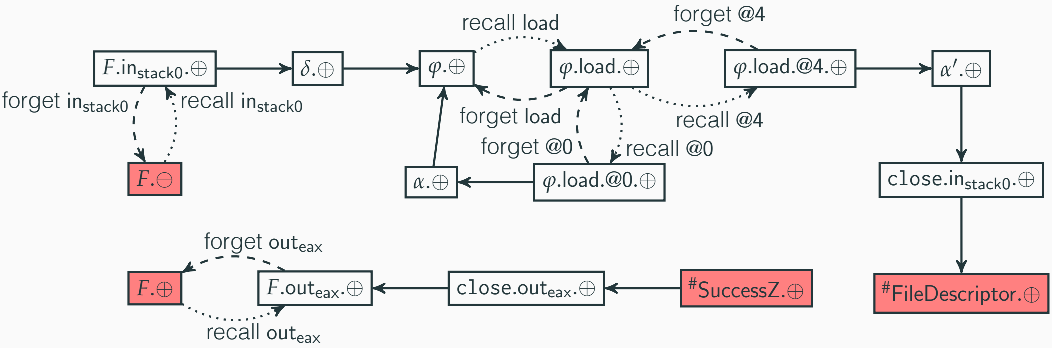
Step 1: From the constraint set, build a graph with an edge for each subtype constraint, and forget/recall-labeled edges describing the derived type variables.

Example, cont'd: Simplifying constraint sets



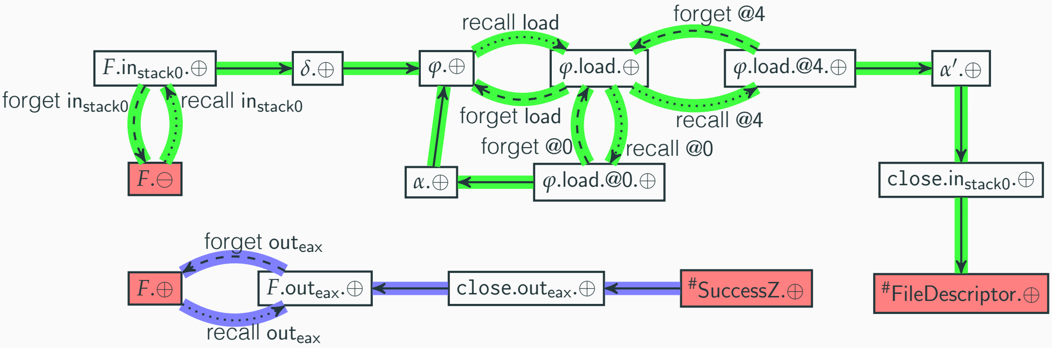
Step 2: Add edges to reify the relation forget $\alpha \cdot$ recall $\alpha = 1$. Lazily instantiate applications of S-Pointer as needed.

Example, cont'd: Simplifying constraint sets



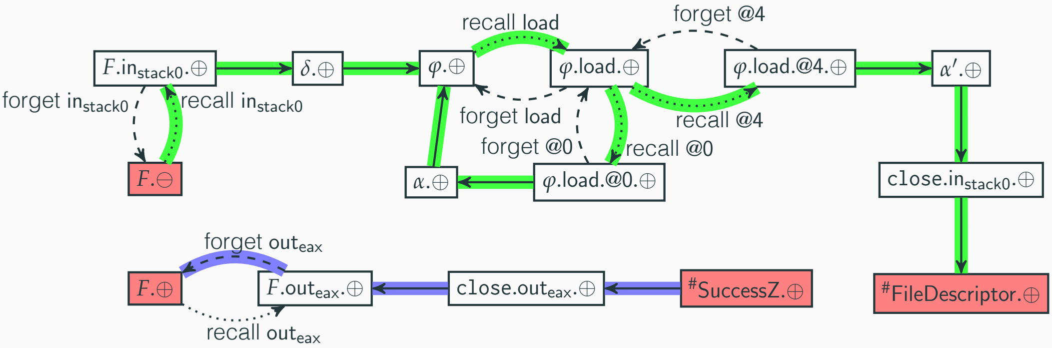
Step 3: Identify the "externally-visible" type variables and constants; call that set $\mathcal{E}$.

Example, cont'd: Simplifying constraint sets



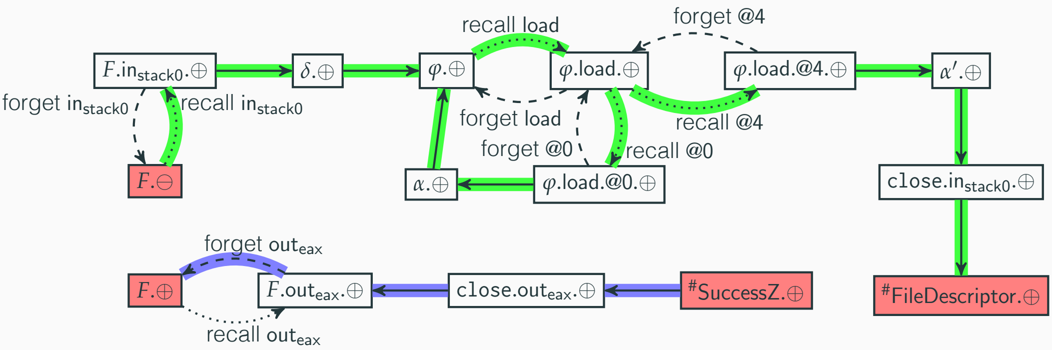
Step 4: Use Tarjan's path-expression algorithm to describe all paths that start and end in $\mathcal{E}$ but only travel through $\mathcal{E}^c$.

Example, cont'd: Simplifying constraint sets



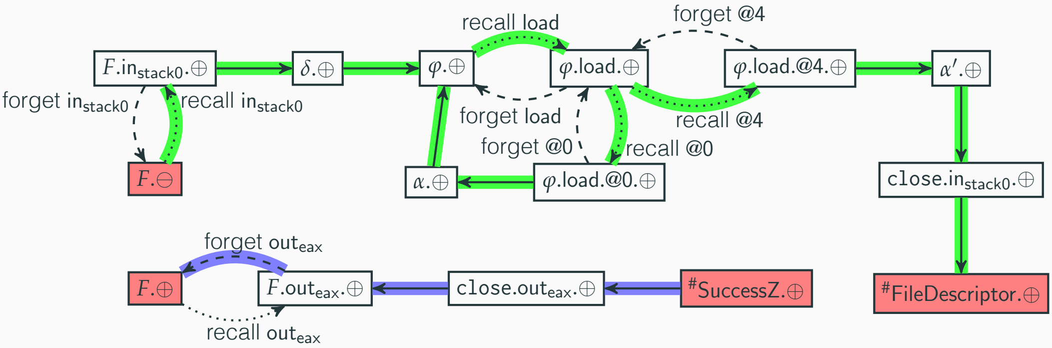
Step 5: Intersect the path expressions with the language $(\text{recall }\_)^*(\text{forget }\_)^*$.

Example, cont'd: Simplifying constraint sets



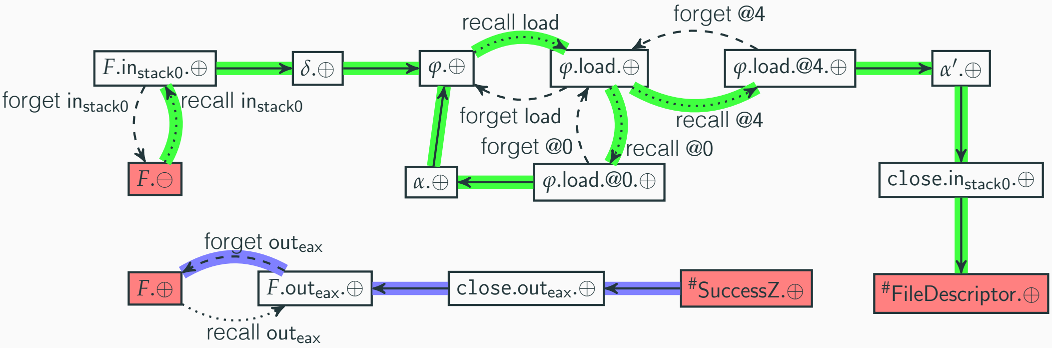
Step 6: Interpret the resulting language as a regular set of subtype constraints. ("forgets" on the right, "recalls" on the left)

Example, cont'd: Simplifying constraint sets



$$
\begin{aligned}
{}^{\#}\text{SuccessZ} &\rightsquigarrow F : && \text{forget out}_{\text{eax}} \\
F &\rightsquigarrow {}^{\#}\text{FileDescriptor} : && \text{recall } \left(\text{in}_{\text{stack0}} \cdot (\text{load} \cdot @0)^* \cdot \text{load} \cdot @4\right)
\end{aligned}
$$

Example, cont'd: Simplifying constraint sets



$$\mathcal{C} = \left\{ \begin{array}{l} {}^{\#}\mathsf{SuccessZ} \sqsubseteq F.\mathsf{out}_{\mathsf{eax}} \\ F.\mathsf{in}_{\mathsf{stack0}}\ (.\mathsf{load}.@0)^{*}\ .\mathsf{load}.@4 \sqsubseteq {}^{\#}\mathsf{FileDescriptor} \end{array} \right\}$$

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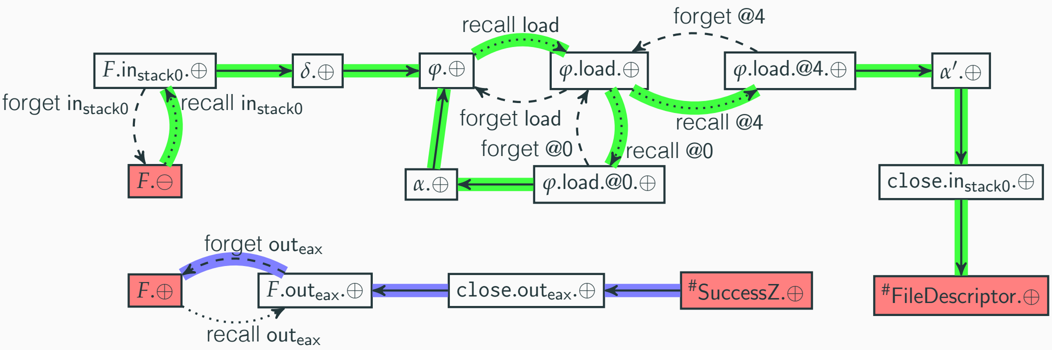

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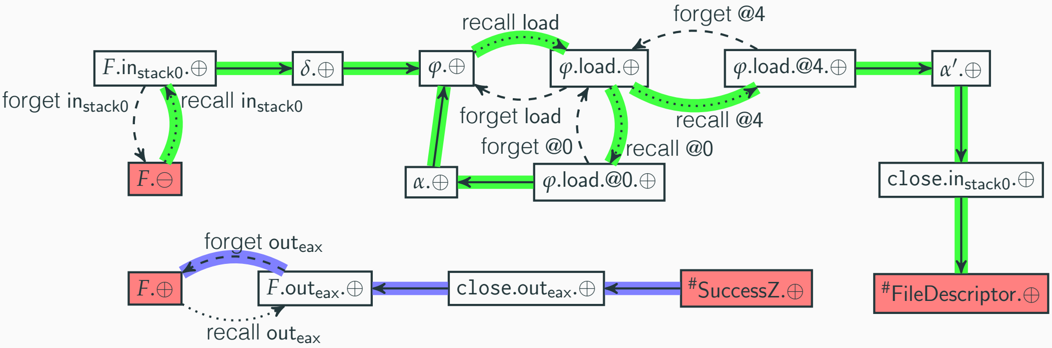

$$\mathcal{C} = \exists\tau.\ \left\{ \begin{array}{l} ^{\#}\mathsf{SuccessZ} \sqsubseteq F.\mathsf{out}_{\mathsf{eax}} \\ F.\mathsf{in}_{\mathsf{stack0}} \sqsubseteq \tau, \quad \tau.\mathsf{load}.@0 \sqsubseteq \tau, \quad \tau.\mathsf{load}.@4 \sqsubseteq {}^{\#}\mathsf{FileDescriptor} \end{array} \right\}$$

Example, cont'd: Getting back to C types

```c
#include <stdlib.h>

struct LL
{
    struct LL * next;
    int handle;
};

int close_last(struct LL * list)
{
    while (list->next != NULL)
    {
        list = list->next;
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```asm
close_last:
    push    ebp
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$$\texttt{close\_last} : \forall F.\ (\exists \tau.\, \mathcal{C}) \Rightarrow F$$

where

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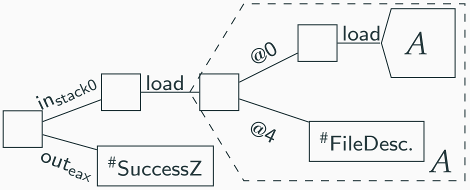

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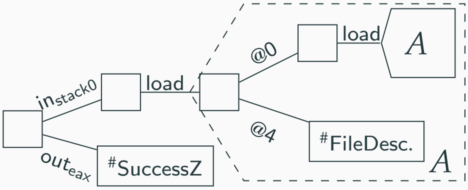


```c
typedef struct Struct_0 {
    struct Struct_0 * field_0;
    int // #FileDescriptor
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} Struct_0;

int // #SuccessZ
close_last(const Struct_0 *);
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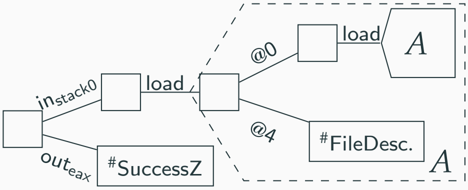


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Evaluation of the technique

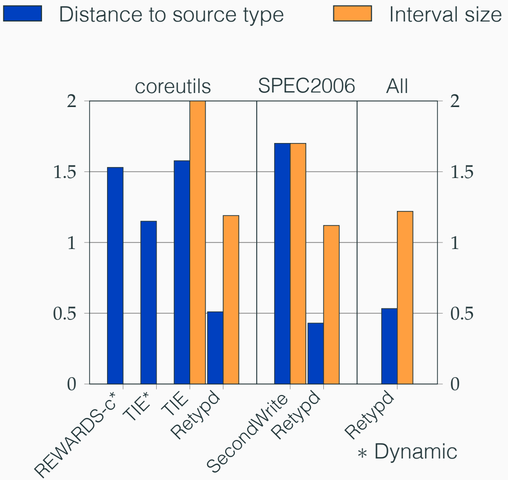
Benchmark suite

Retypd was evaluated on a suite of 160 optimized 32-bit x86 binaries with debug information removed. Separate optimized debug builds were used to establish ground truth.

The benchmark suite included:

- A suite of real-world Windows binaries compiled with Visual Studio.
- The SPEC2006 binaries used to evaluate type inference for SecondWrite.
- The coreutils binaries used to evaluate TIE.

Does it work?



Retypd generates types that are:

- More accurate
- More tightly constrained

than existing approaches.

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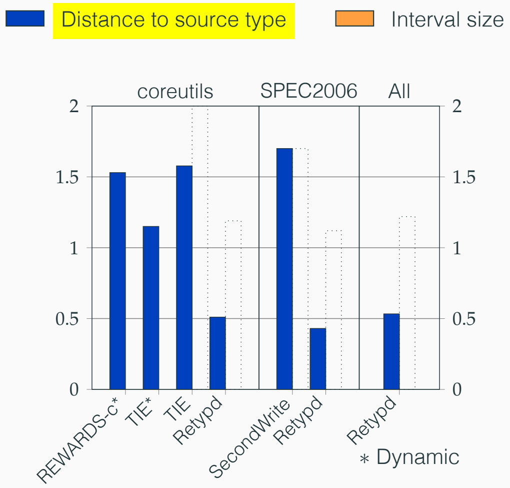

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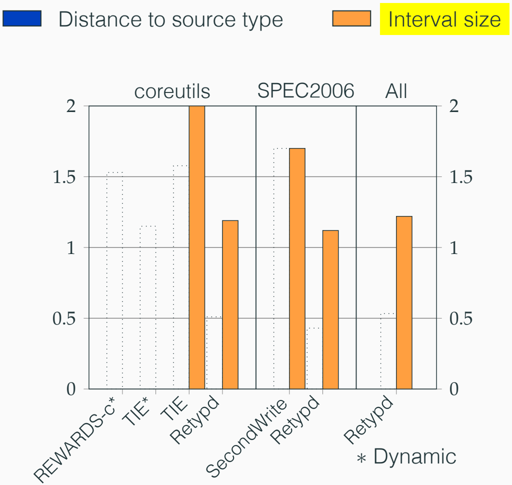

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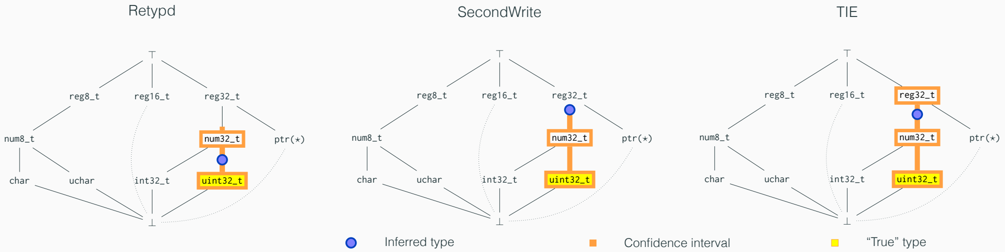
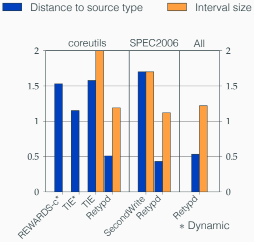
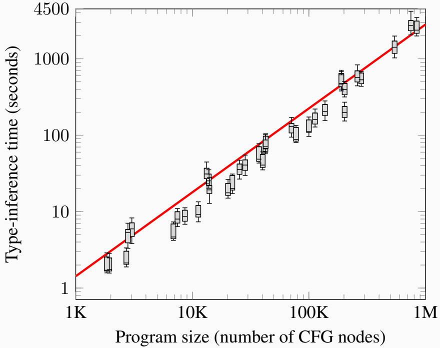
Visualizing the precision improvement

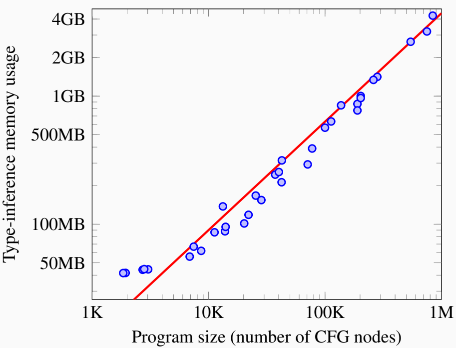




Performance measurements

Real-world performance scales like $N^{1.078}$ in time and $N^{0.882}$ in memory.





Summary

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    - But we can do pretty well anyway.
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    - Subtypes
    - Recursive types
    - Polymorphic functions
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References

K. ElWazeer, K. Anand, A. Kotha, M. Smithson, and R. Barua. Scalable variable and data type detection in a binary rewriter. In Proceedings of the 34th ACM SIGPLAN conference on Programming Language Design and Implementation (PLDI), volume 48, pages 51–60. ACM, 2013.

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Adding the missing edges

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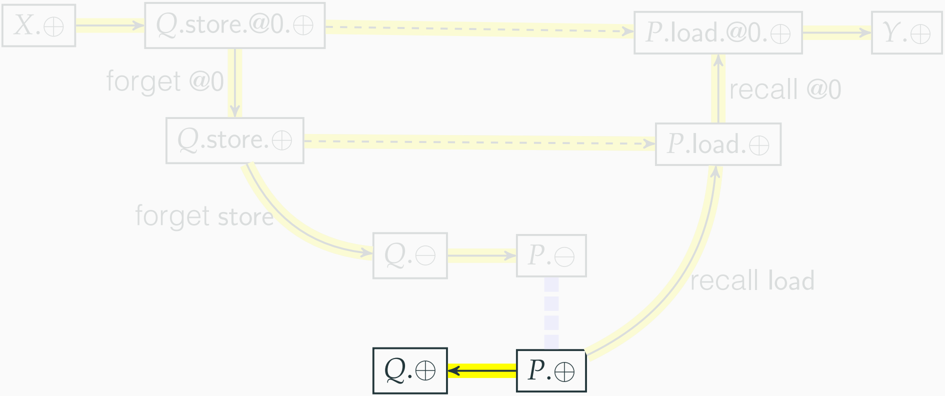

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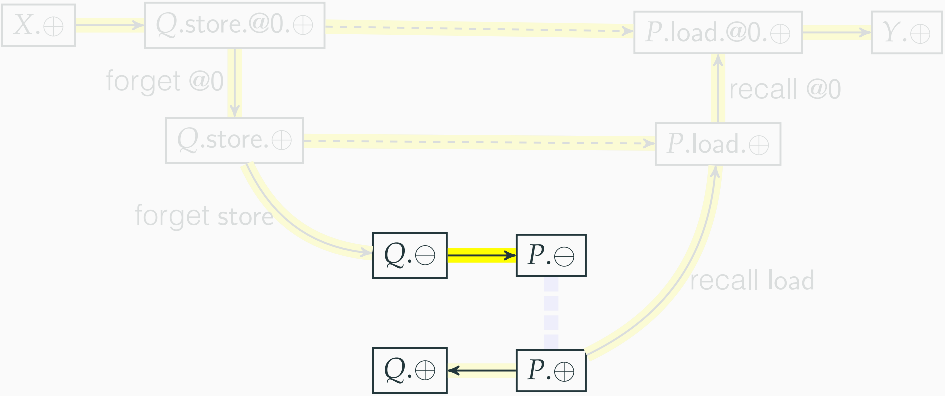

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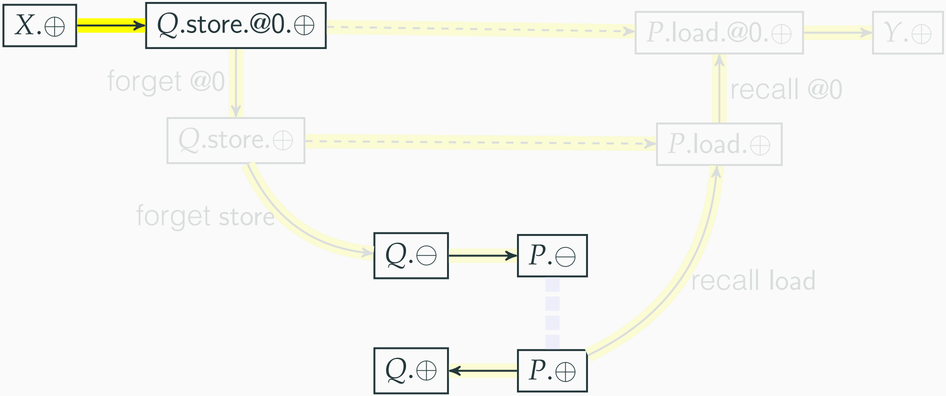

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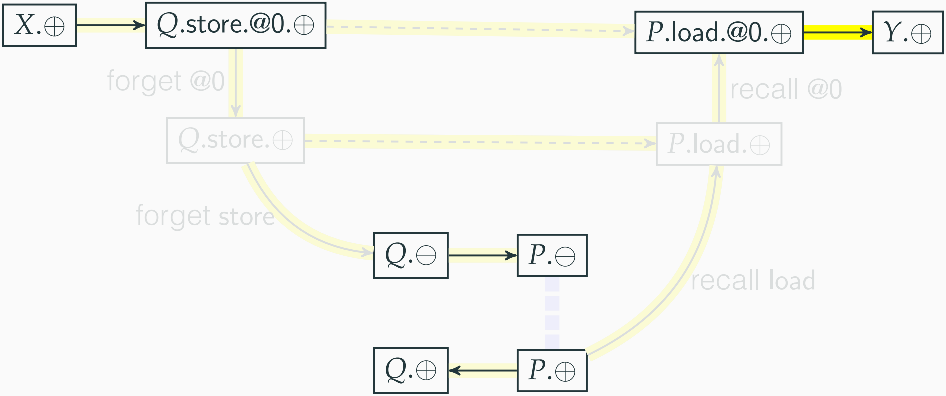

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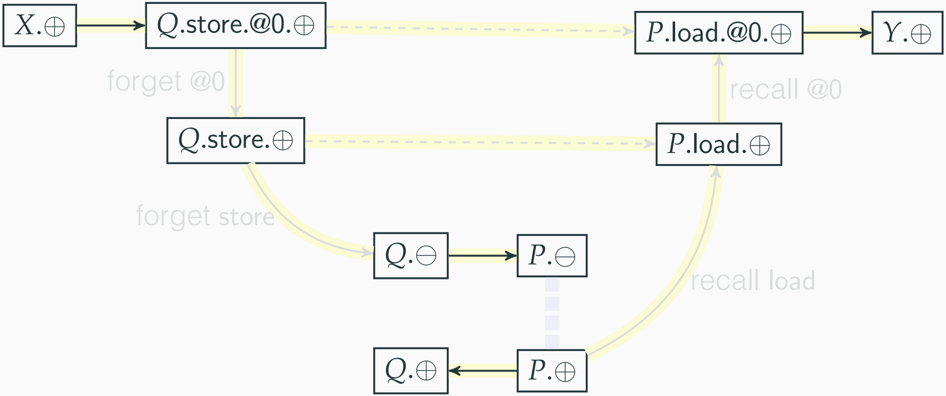

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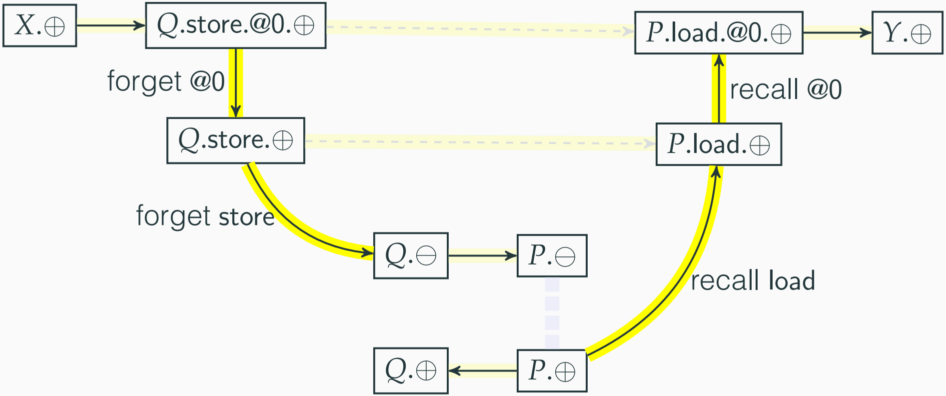

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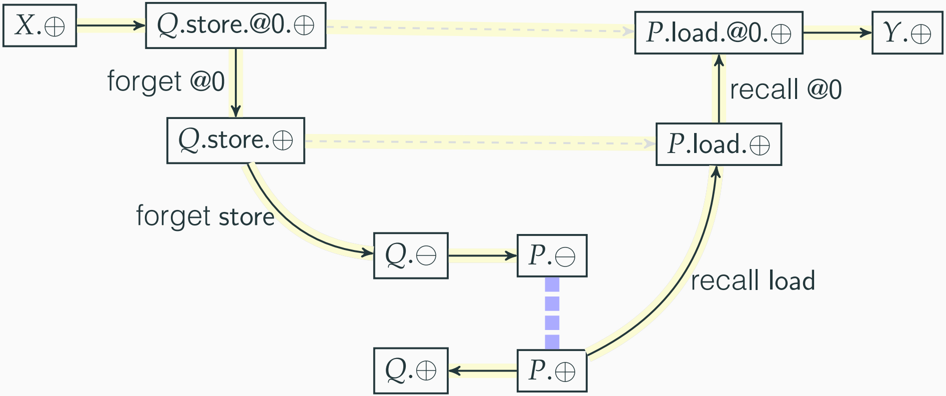

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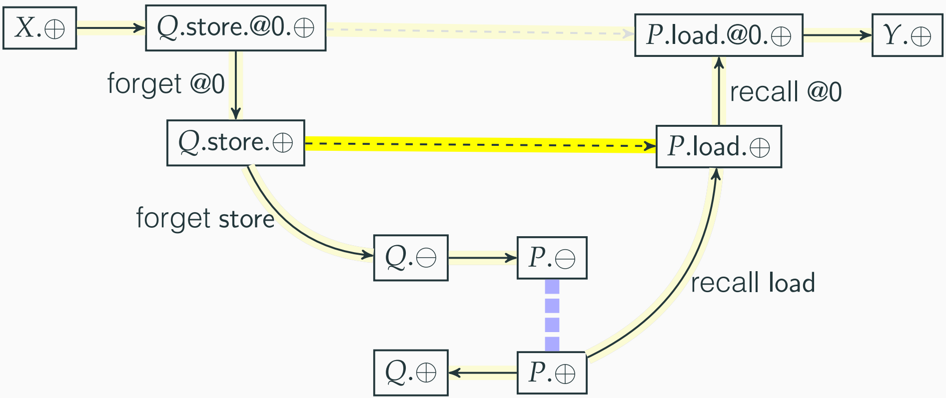

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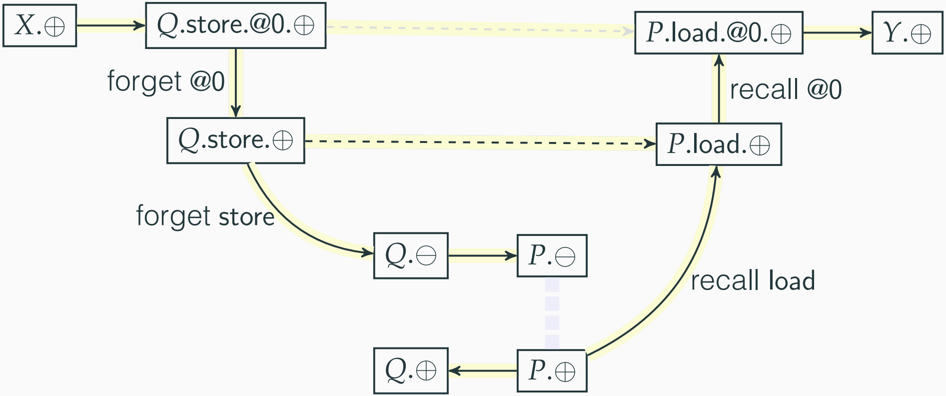

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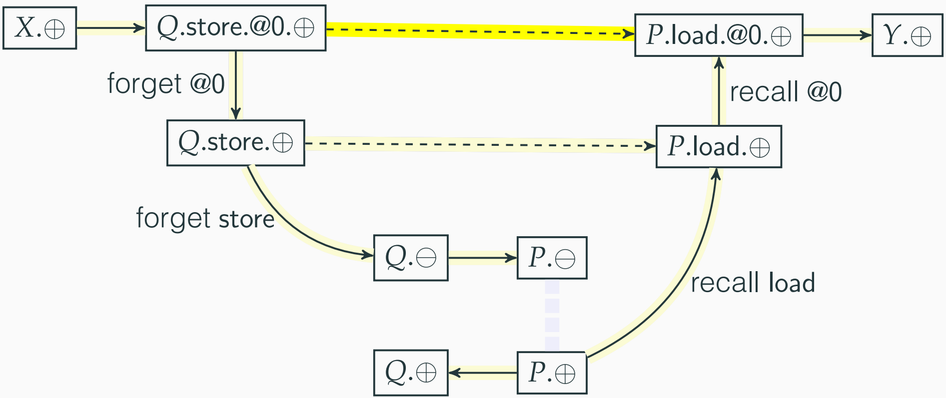

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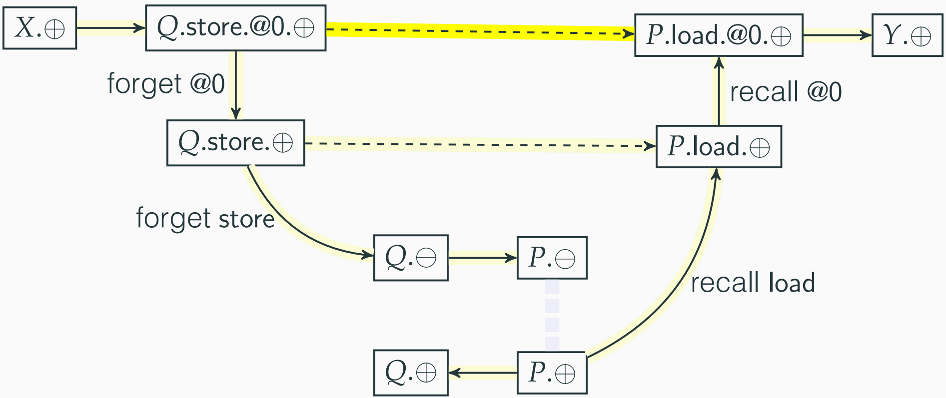

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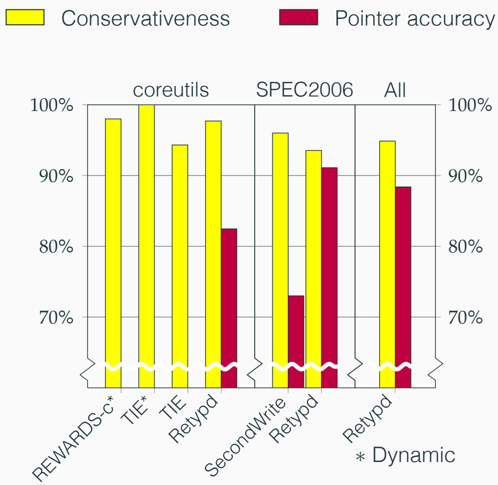

Retypd generates types that:

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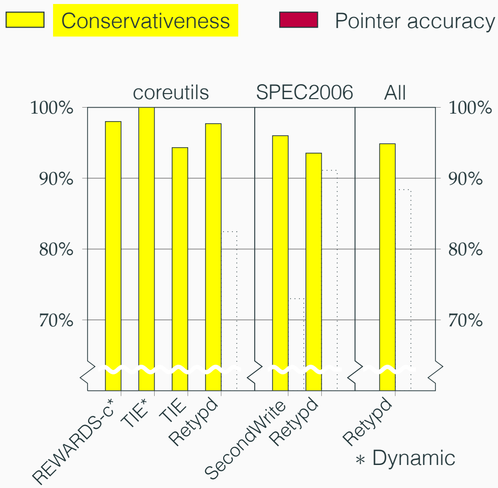

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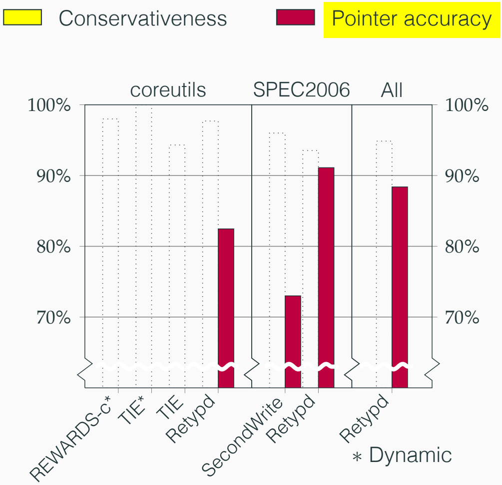

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