Design and Implementation of Sparse Global Analyses for C-like Languages

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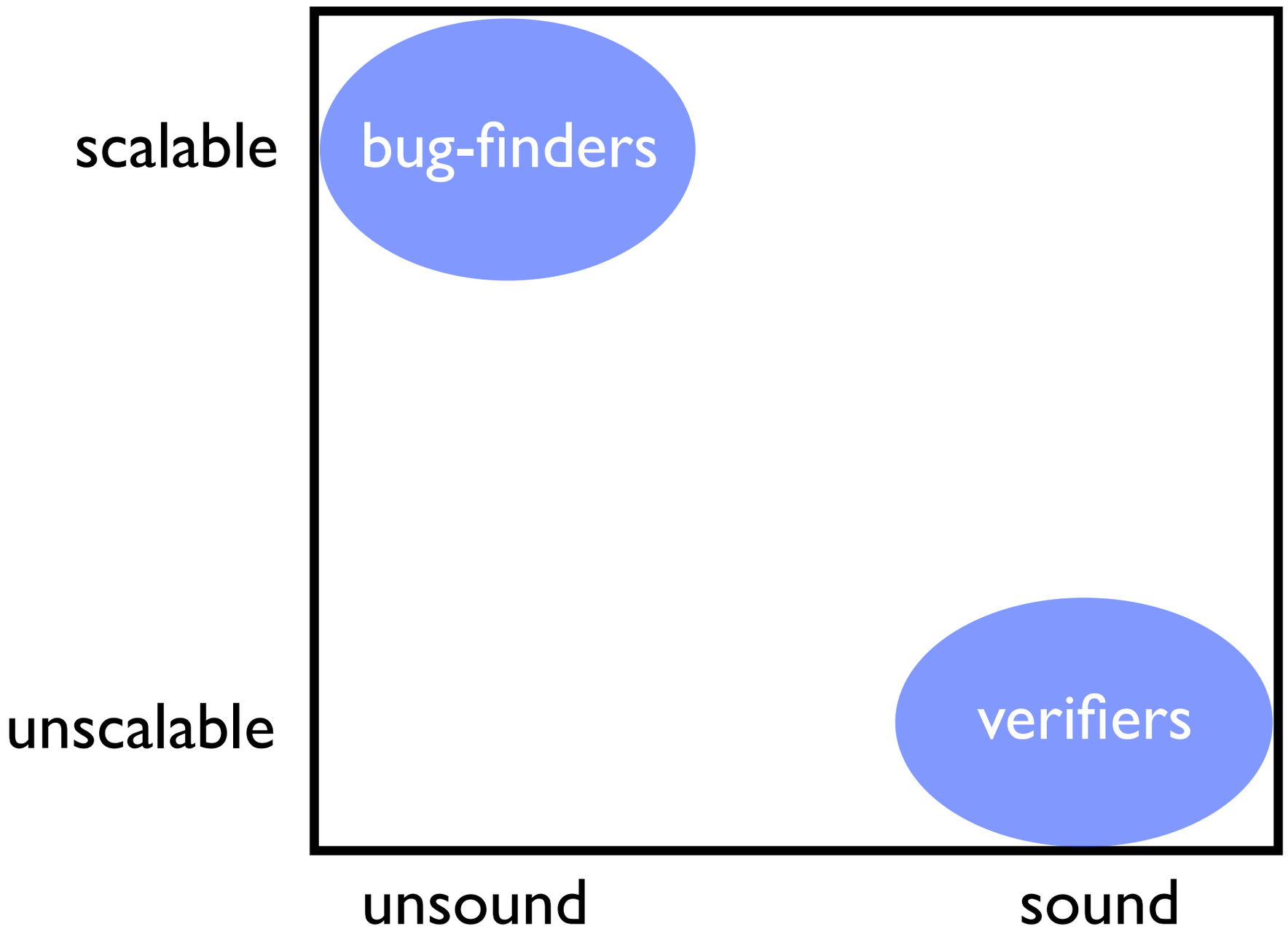
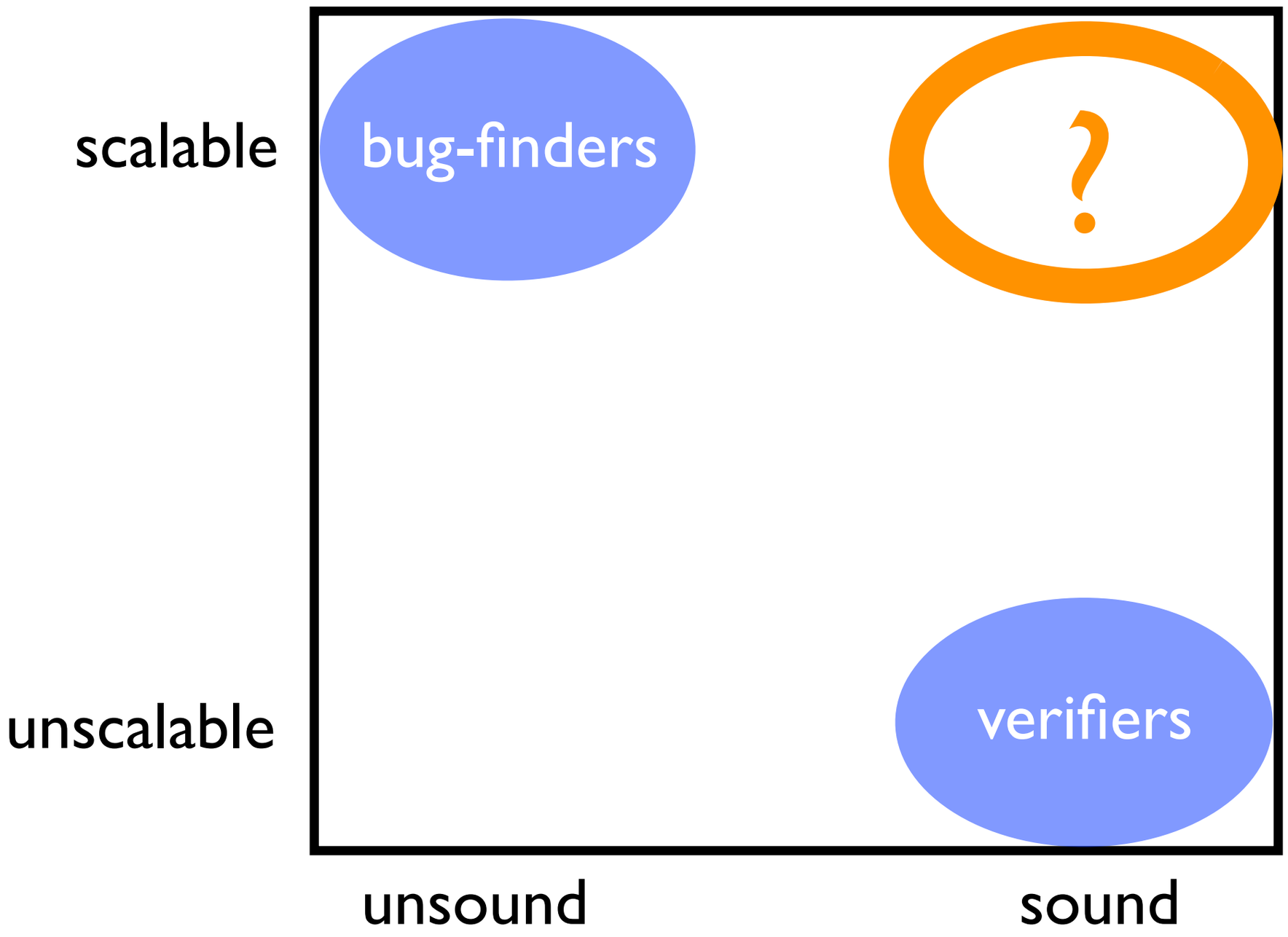
Seoul National University

PLDI 2012 @ Beijing, China

Dichotomy in Static Analysis



Dichotomy in Static Analysis



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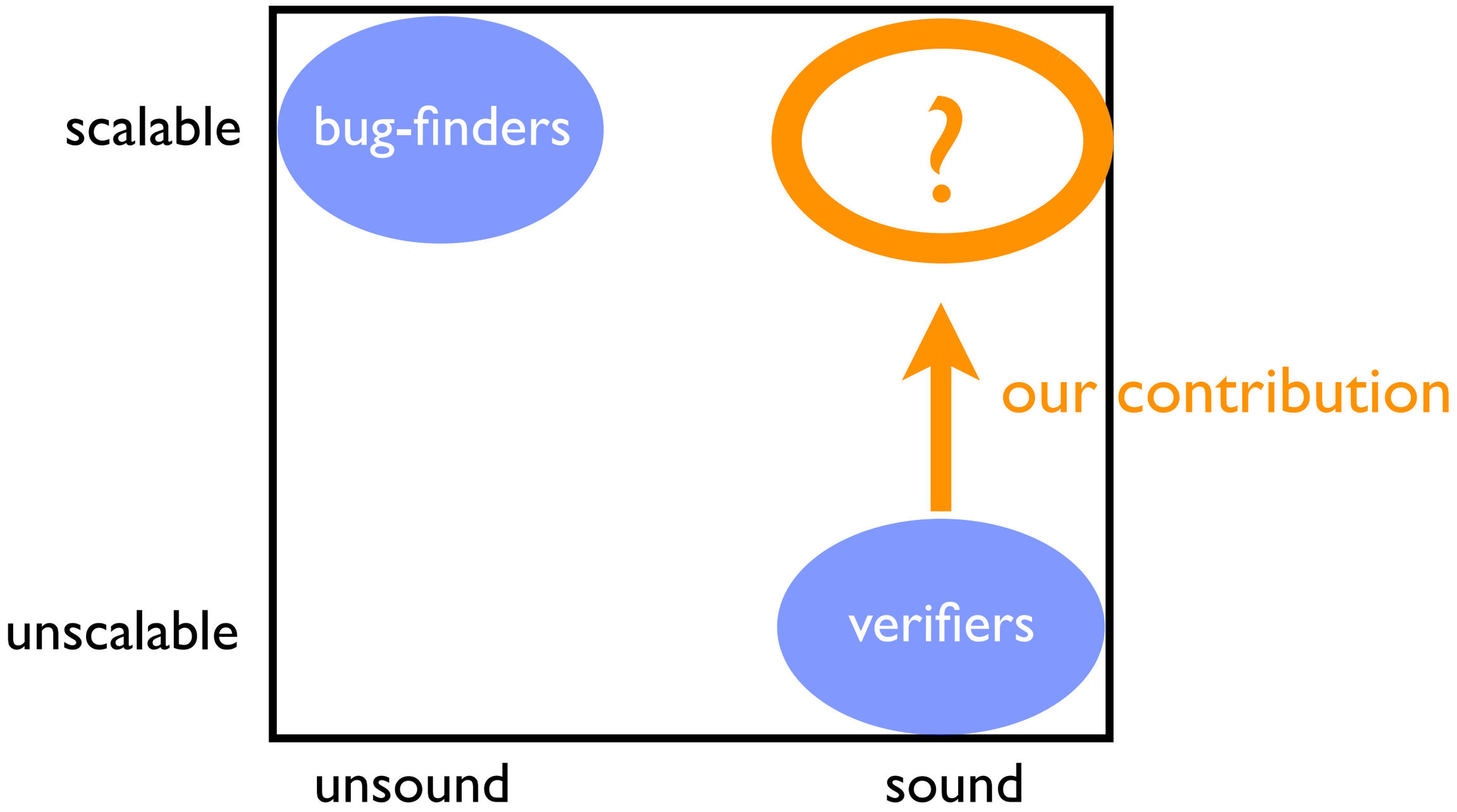


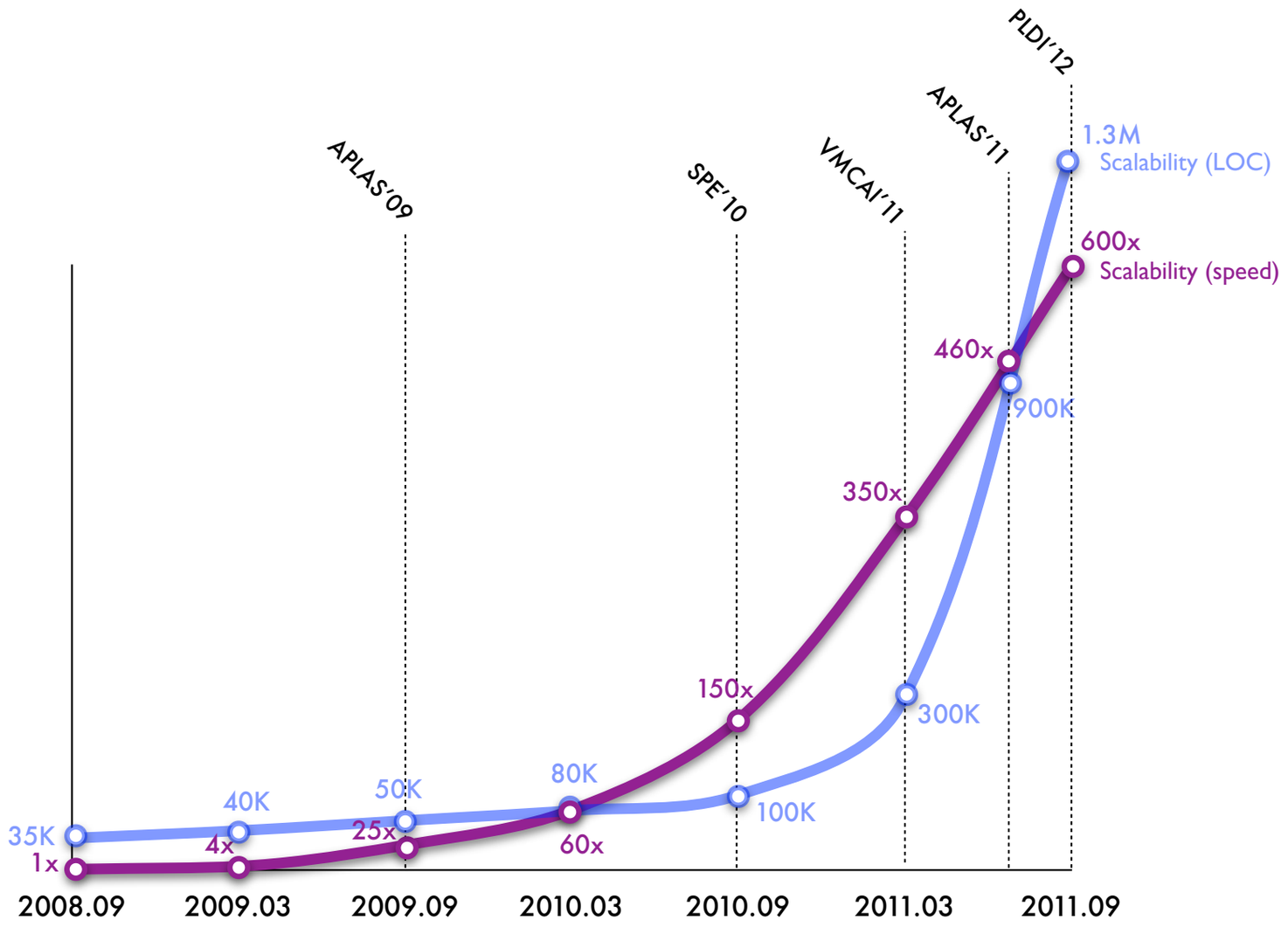
Our Story

- In 2007, we commercialized Sparrow The Early Bird
  - memory-bug-finding tool for full C, non domain-specific
  - designed in abstract interpretation framework
  - sound in design, unsound yet scalable in reality
- Realistic workbench available
  - “let’s try to scale-up its sound & global analysis version”

Scalability Improvement

Sparrow
The Early Bird

sound & global analysis version



- < 1.4M in 10hr with intervals
- < 0.14M in 20hrs with octagons

Precision-Preserving Sparse Analysis Framework

baseline analysis

$$\hat{F} : \hat{D} \to \hat{D}$$

sparsify $\Longrightarrow$

"sparse" version

$$\hat{F}_s : \hat{D} \to \hat{D}$$

$$fix\,\hat{F} \quad \overset{\text{still}}{=} \quad fix\,\hat{F}_s$$

General for AI-based analyzers for C-like languages

Sparse Analysis Framework

- "Right Part at Right Moment"
- "Full Exploitation"
- enabled by Abstract Interpretation theory

Program

$\langle \mathbb{C}, \hookrightarrow \rangle$

- $\mathbb{C}$: set of program points
- $\hookrightarrow \subseteq \mathbb{C} \times \mathbb{C}$: control flow relation

$c' \hookrightarrow c$ (c is the next program point to c')

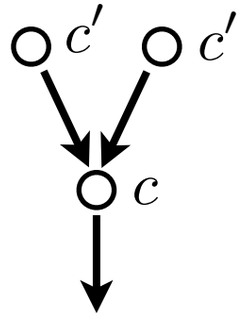
Baseline Analysis

- One abstract state $\in \hat{\mathbb{S}}$ that subsumes all reachable states at each program point

$$
\begin{array}{rcl}
[\![\hat{P}]\!] \in \mathbb{C} \to \hat{\mathbb{S}} & = & \mathit{fix}\,\hat{F} \\
\mathbb{S} & = & \mathbb{L} \to \mathbb{V}
\end{array}
$$

- Abstract semantic function

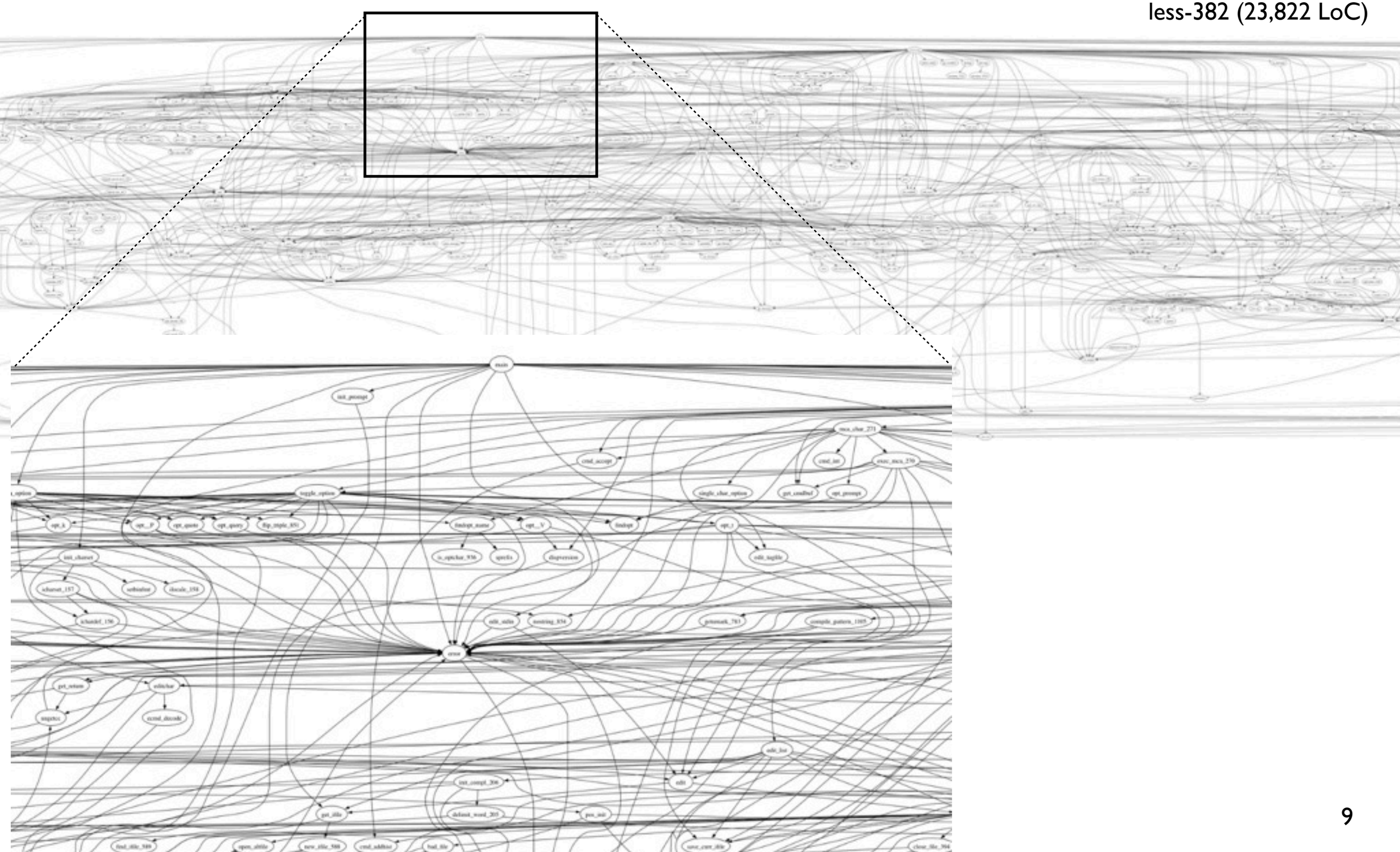
$$
\begin{array}{rcl}
\hat{F} & \in & (\mathbb{C} \to \hat{\mathbb{S}}) \to (\mathbb{C} \to \hat{\mathbb{S}}) \\
\hat{F}(\hat{X}) & = & \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \hookrightarrow c} \hat{X}(c'))
\end{array}
$$



$\hat{f}_c \in \hat{\mathbb{S}} \to \hat{\mathbb{S}}$: abstract semantics at point c

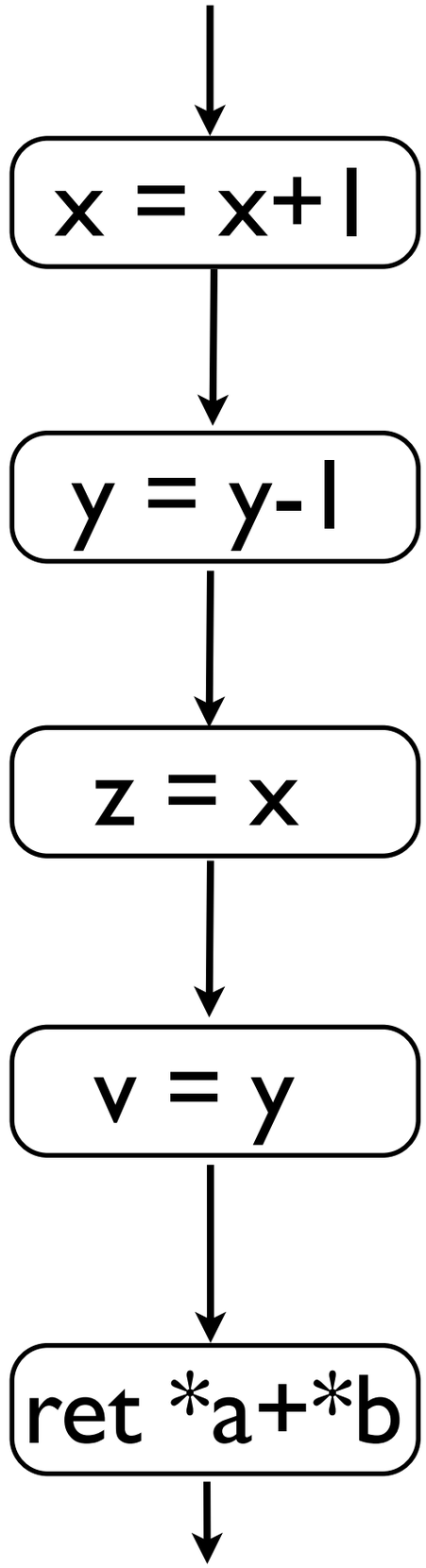
Direct Implementation (convention) Too Weak To Scale

less-382 (23,822 LoC)



"Sparsifying" the Analysis

"Right Part at Right Moment"



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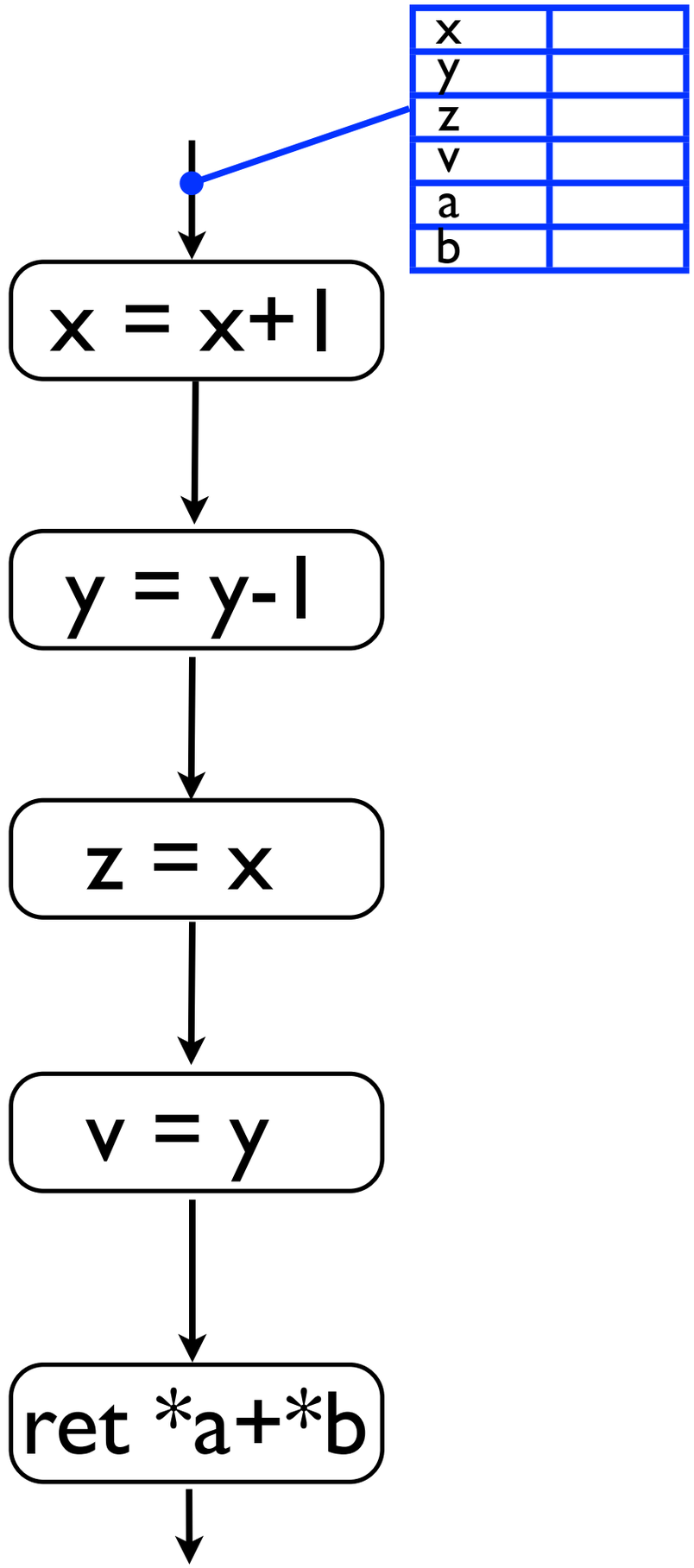

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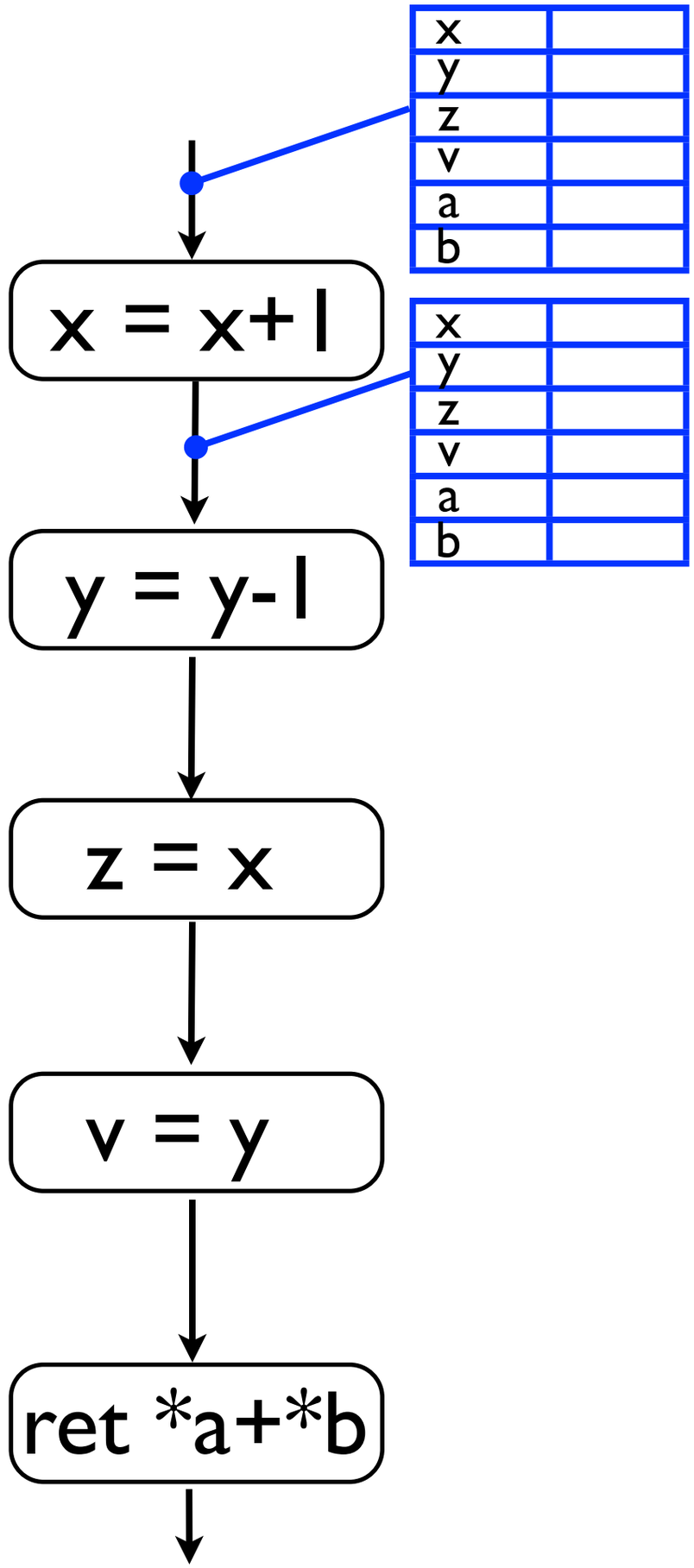

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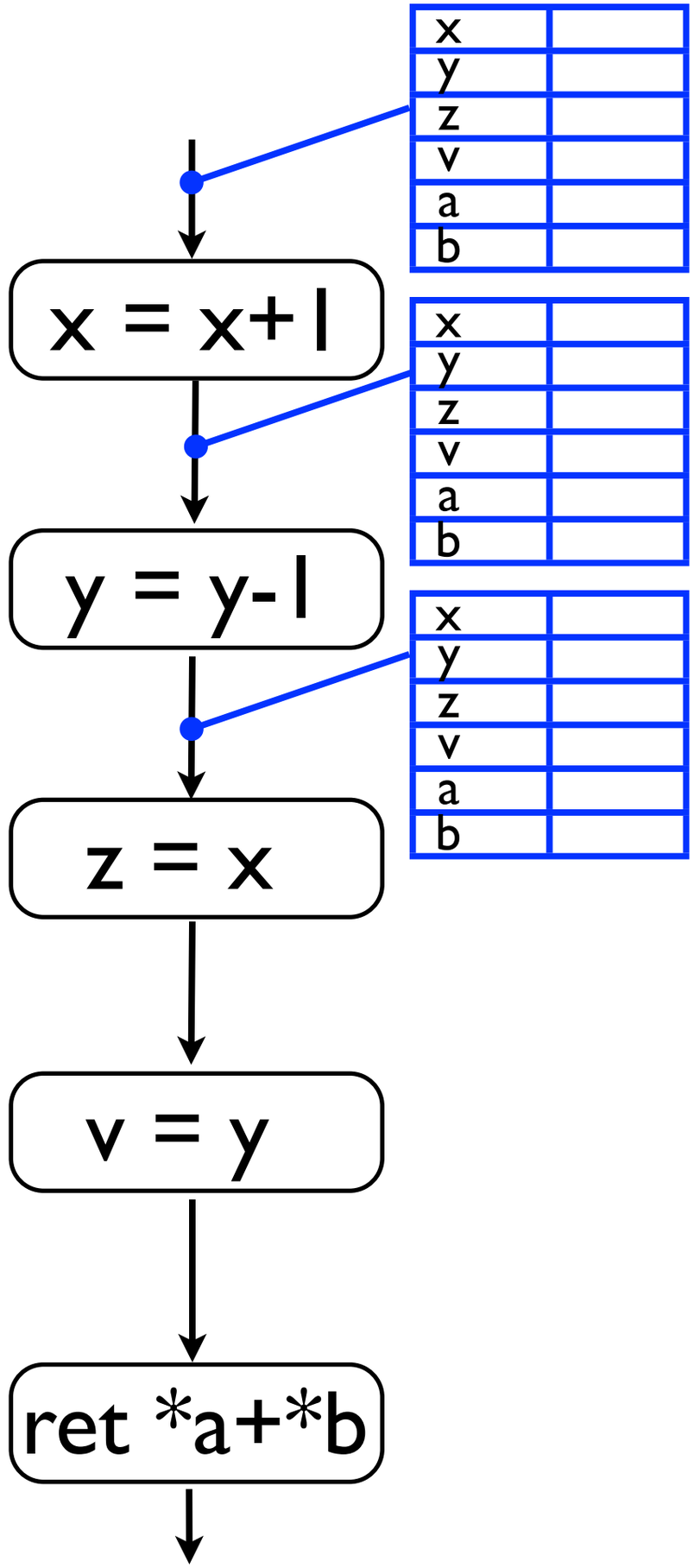

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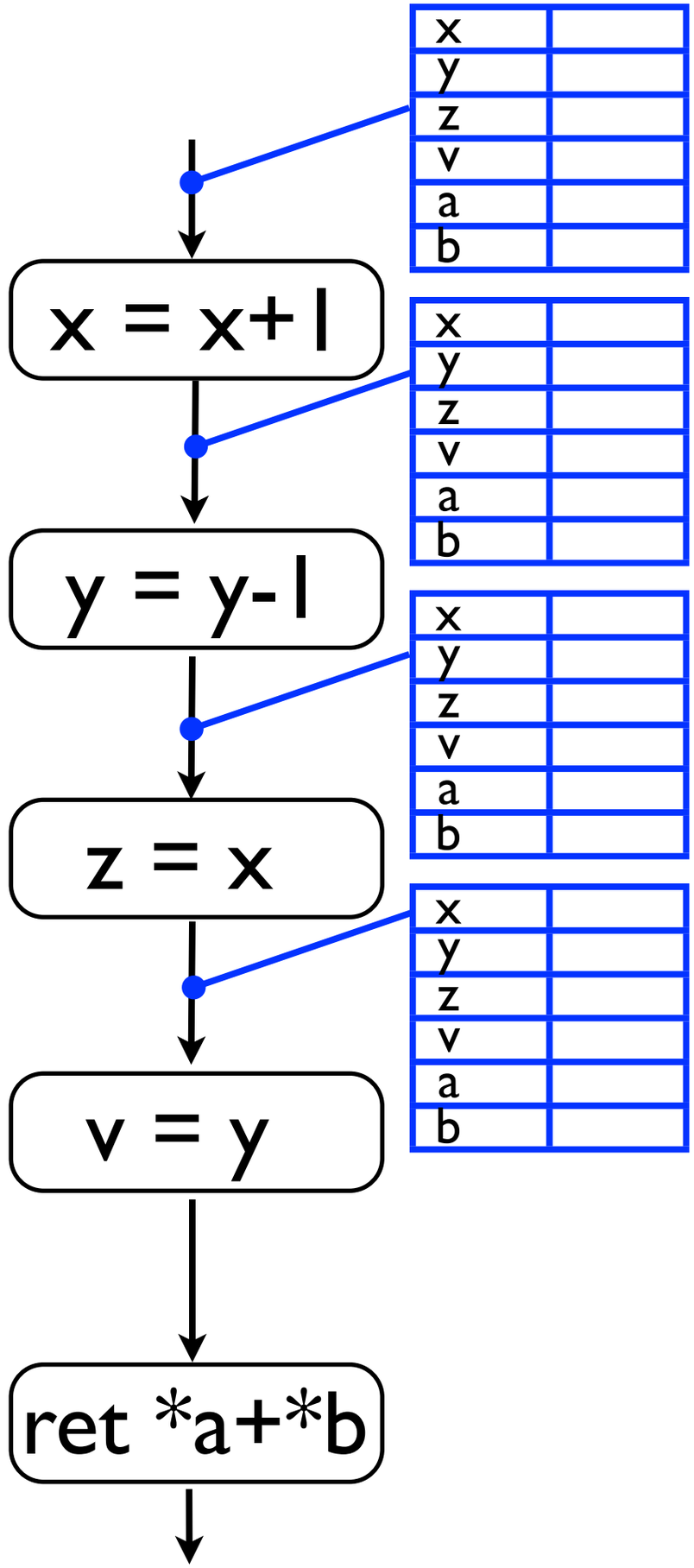

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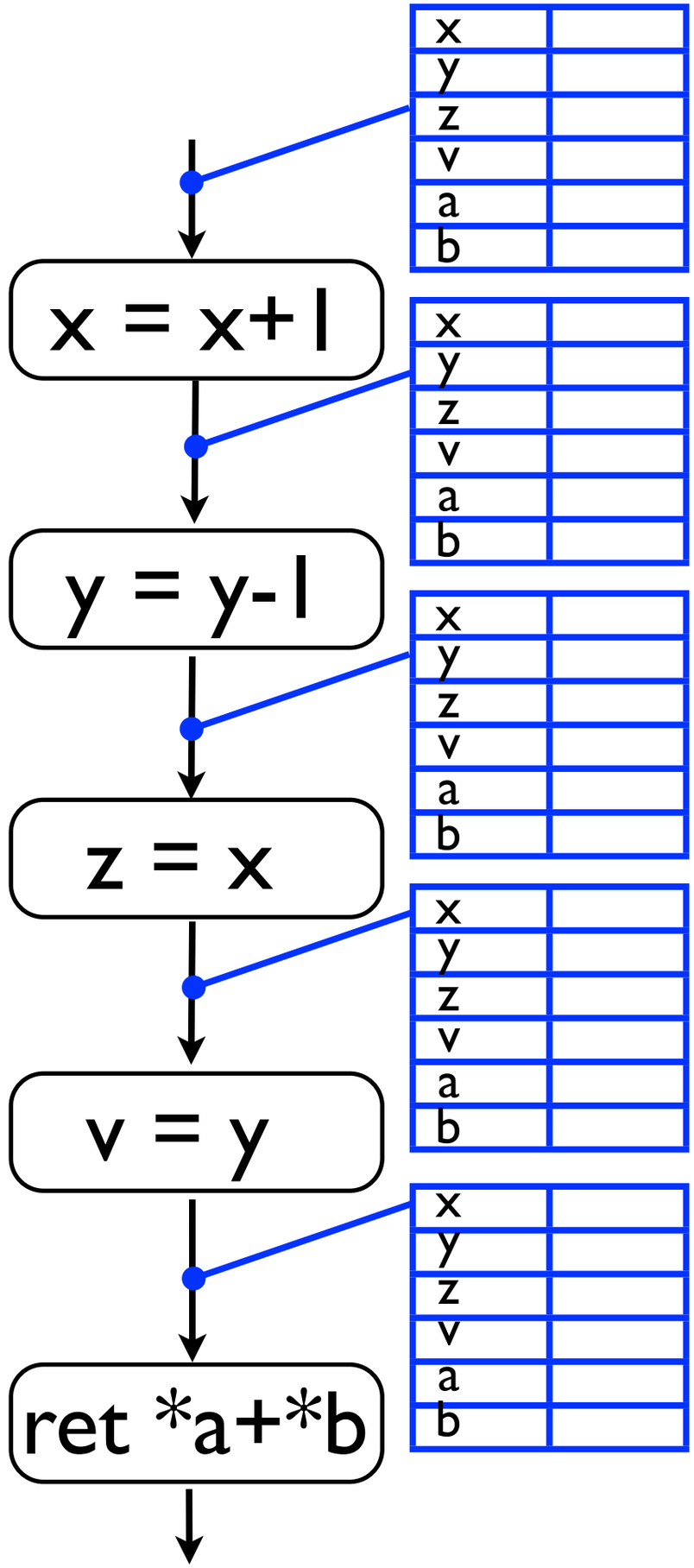

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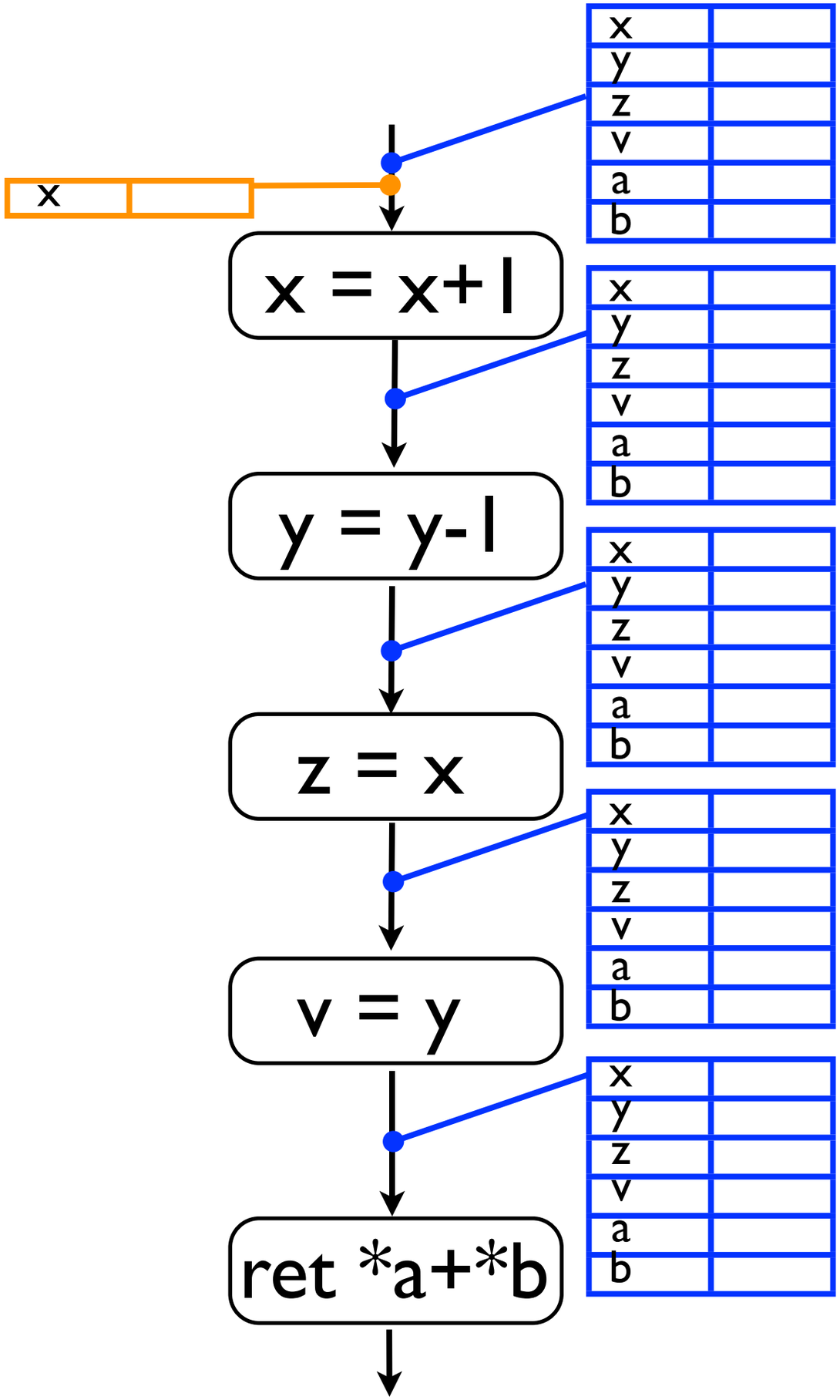

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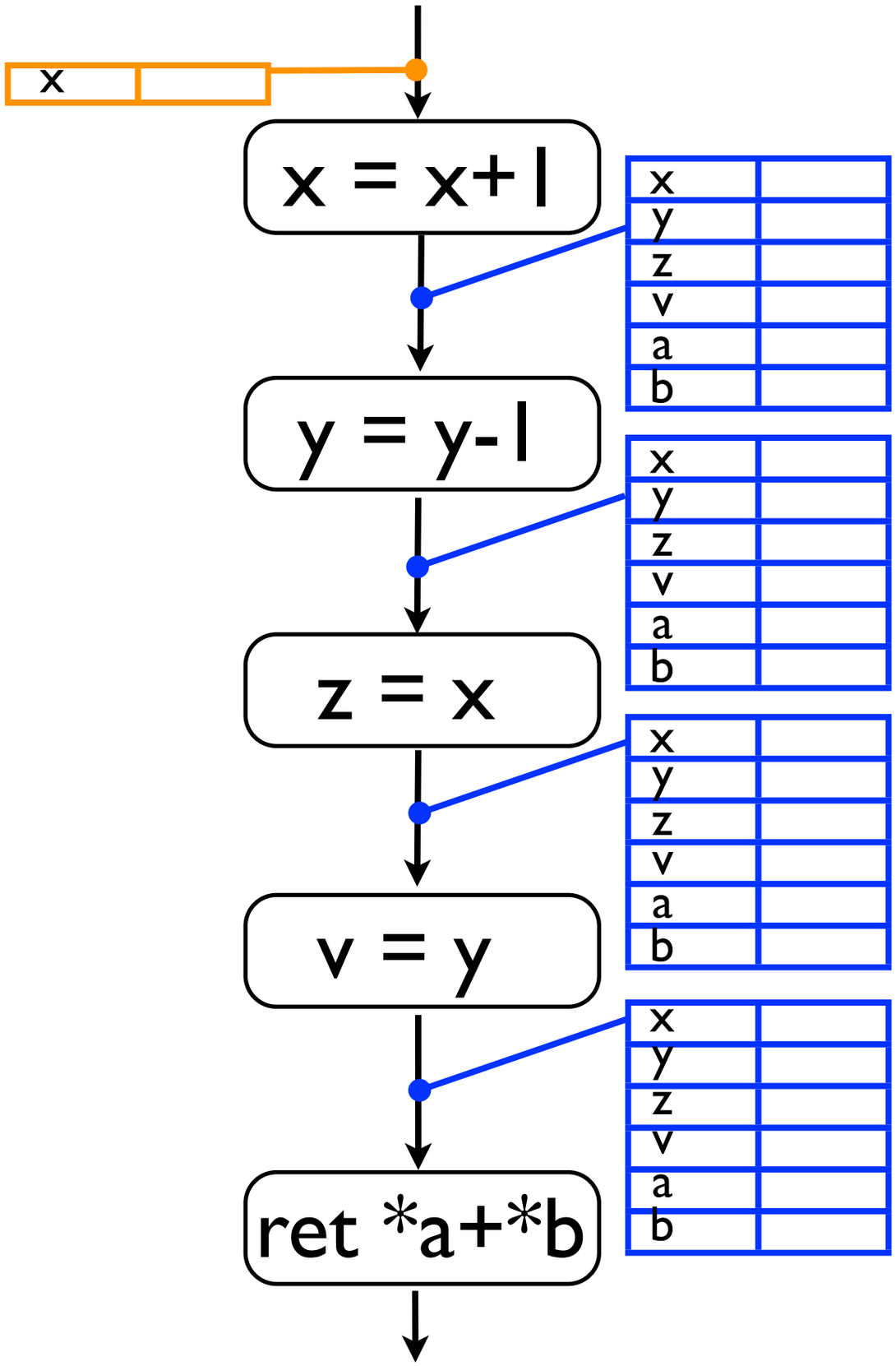

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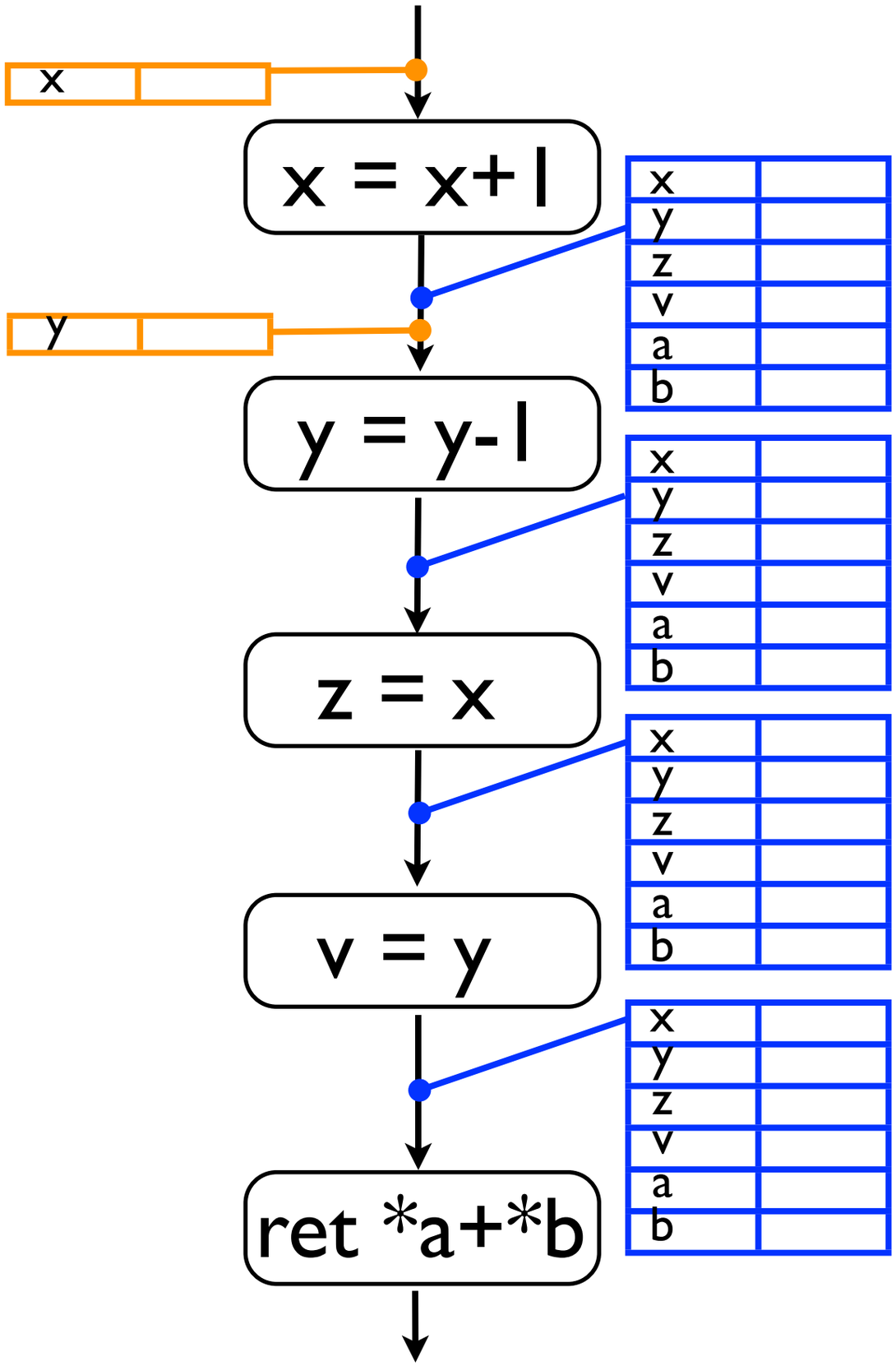

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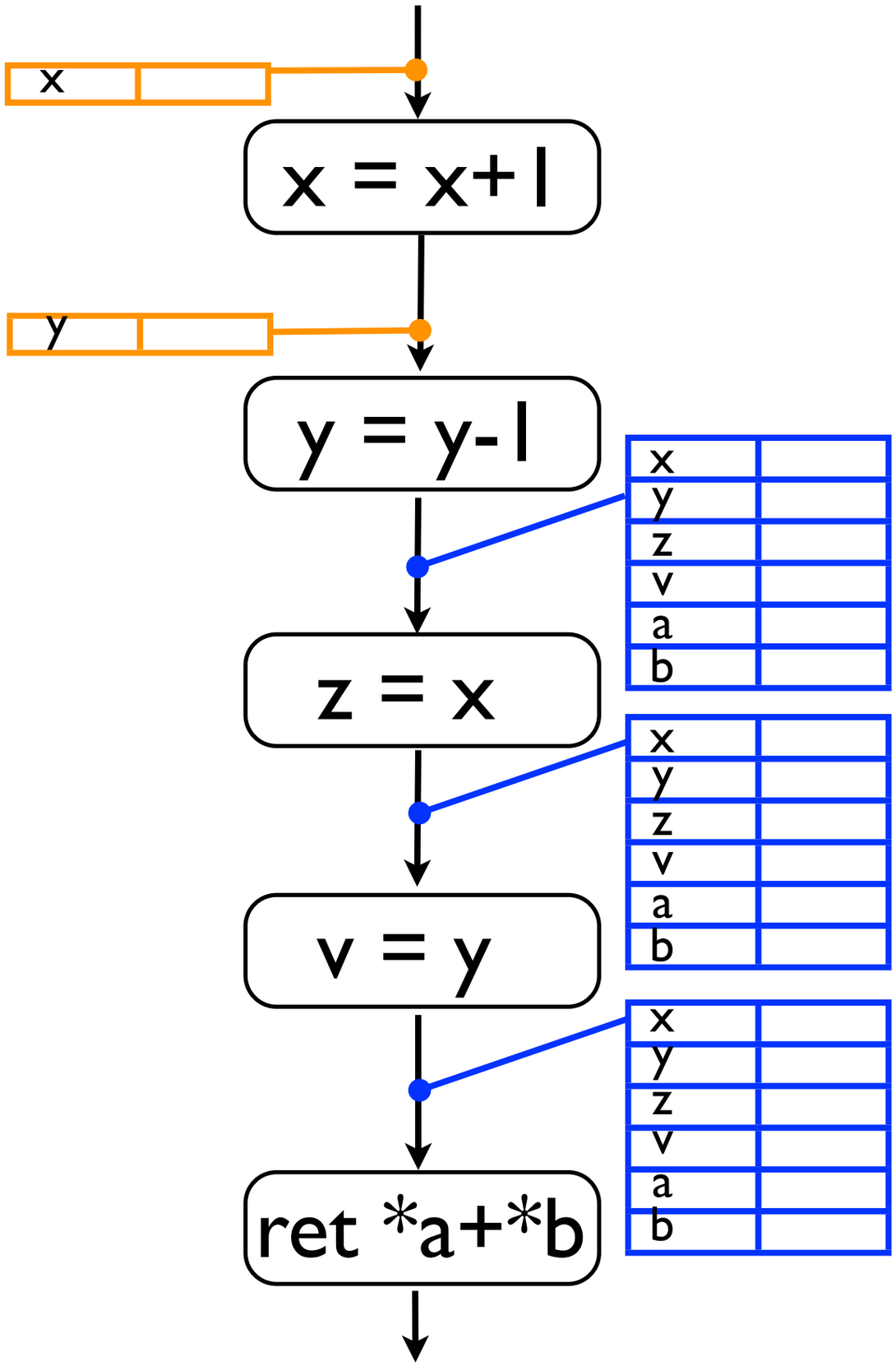

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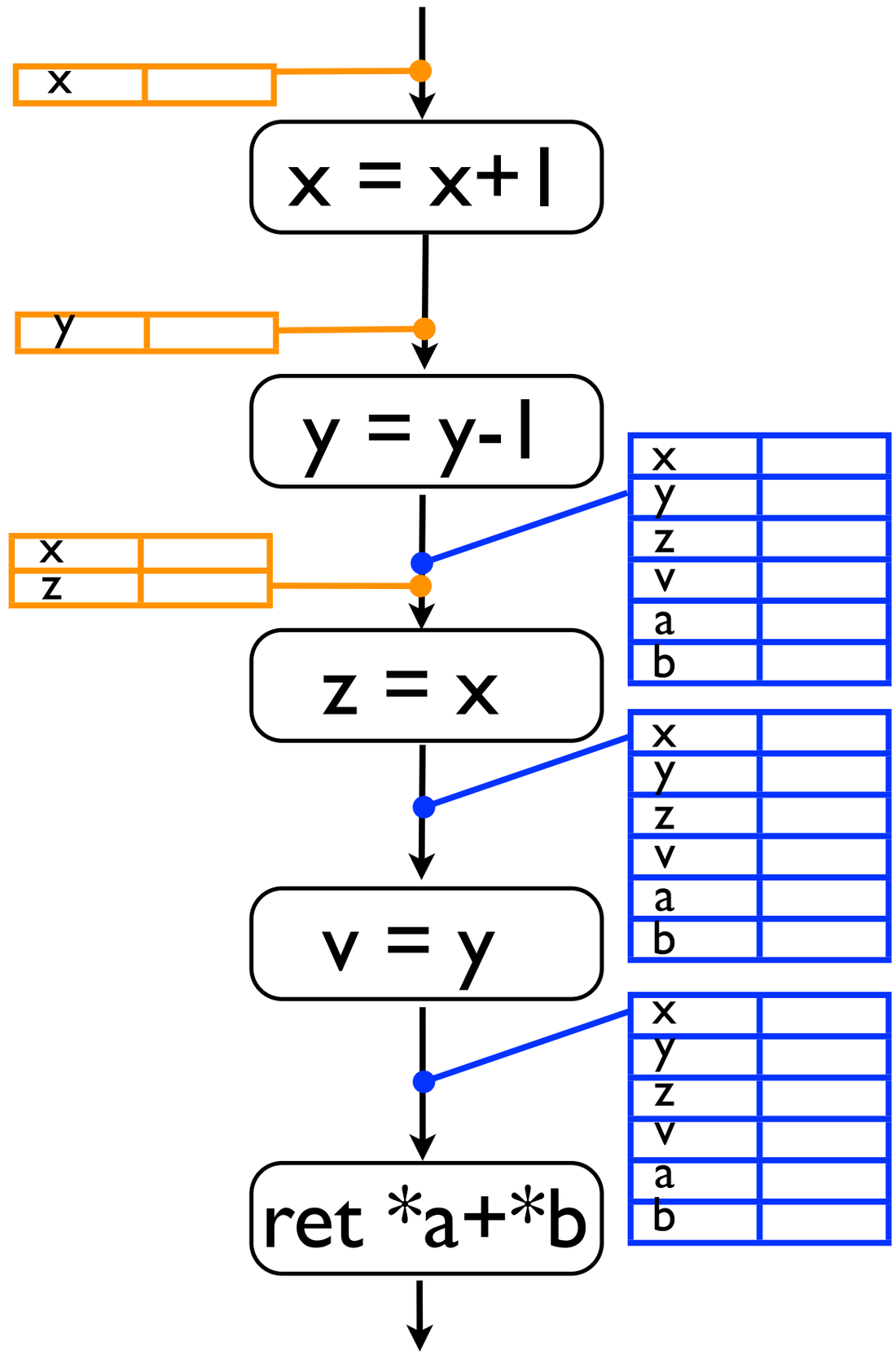

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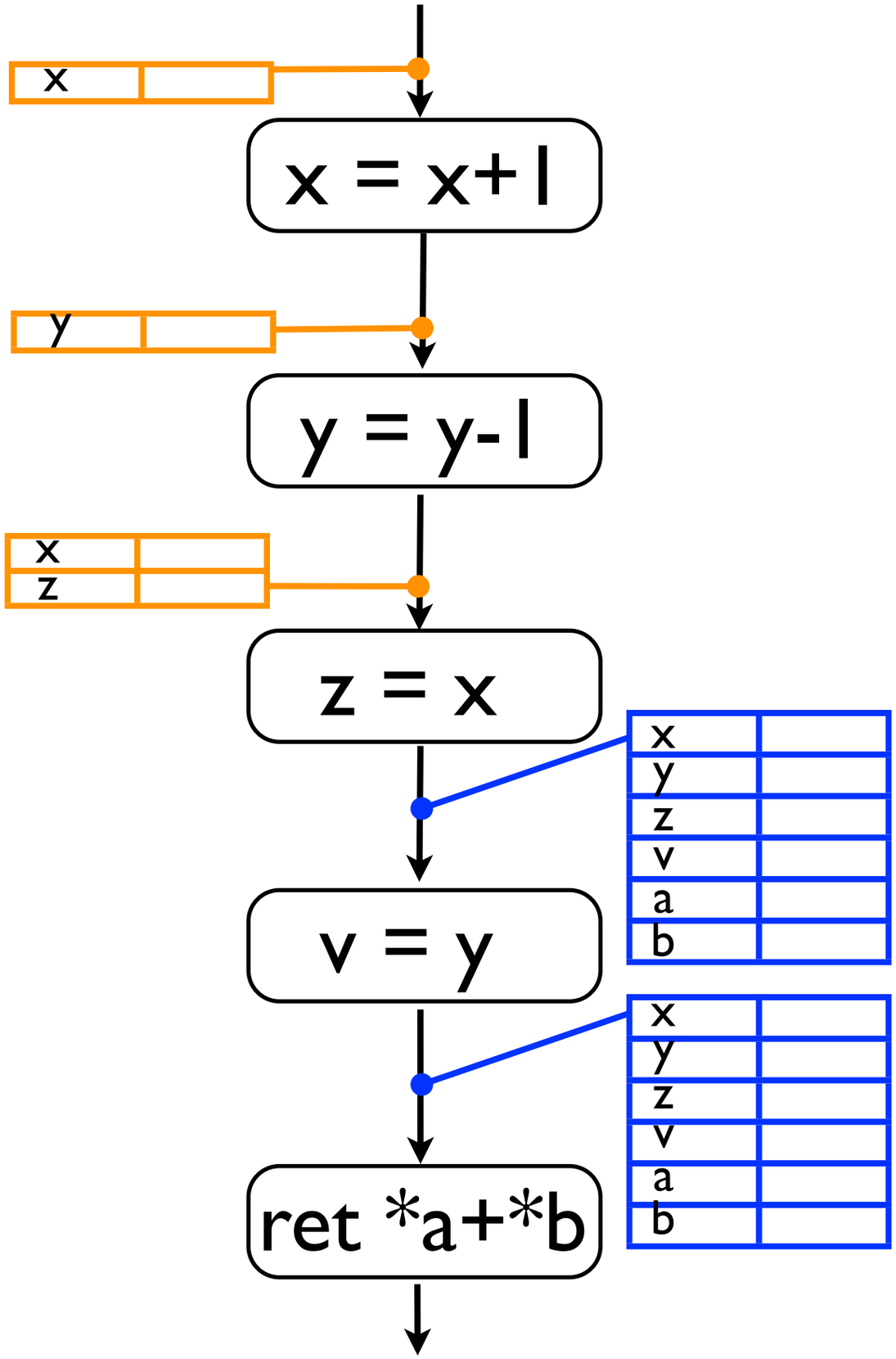

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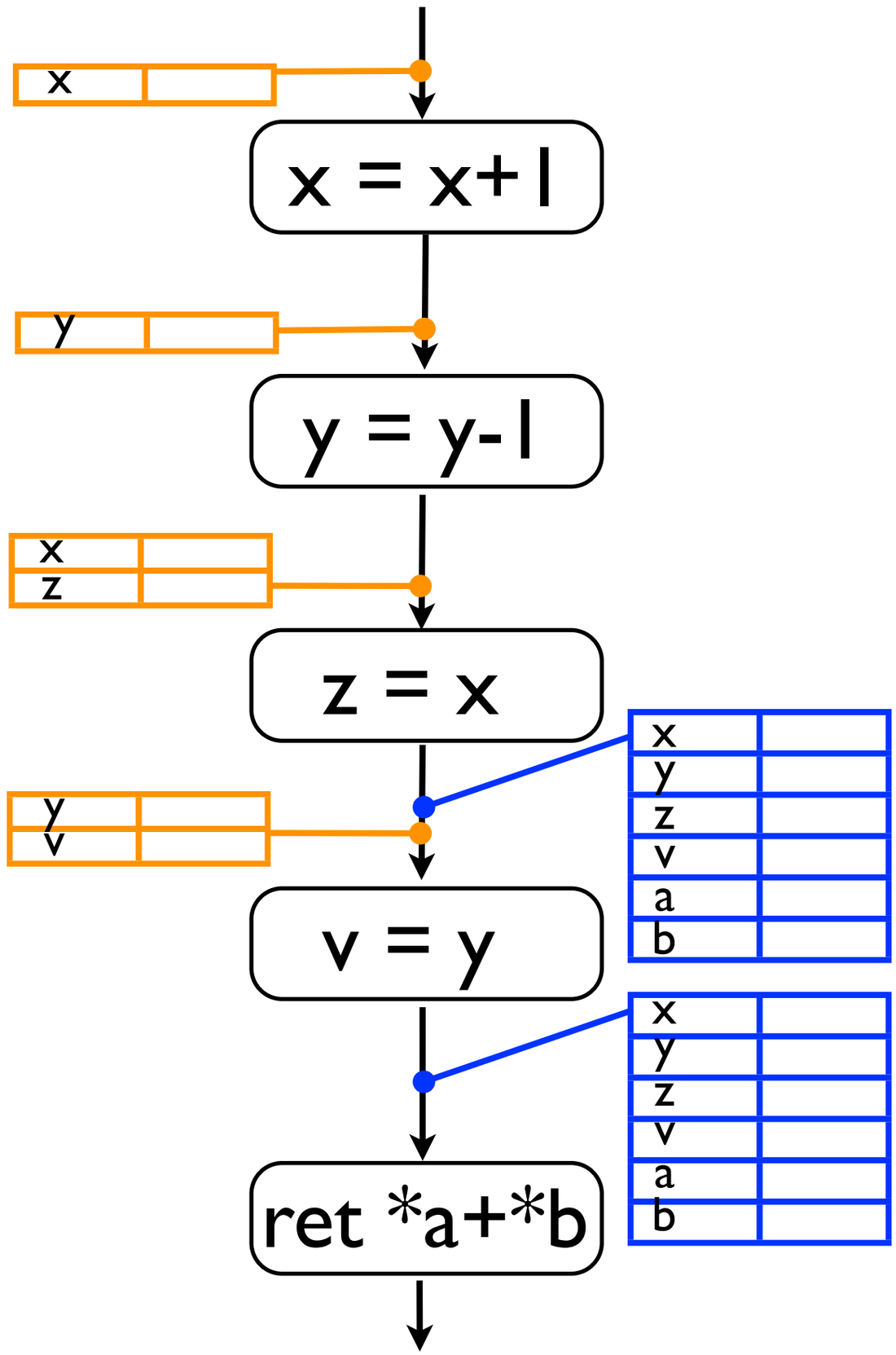

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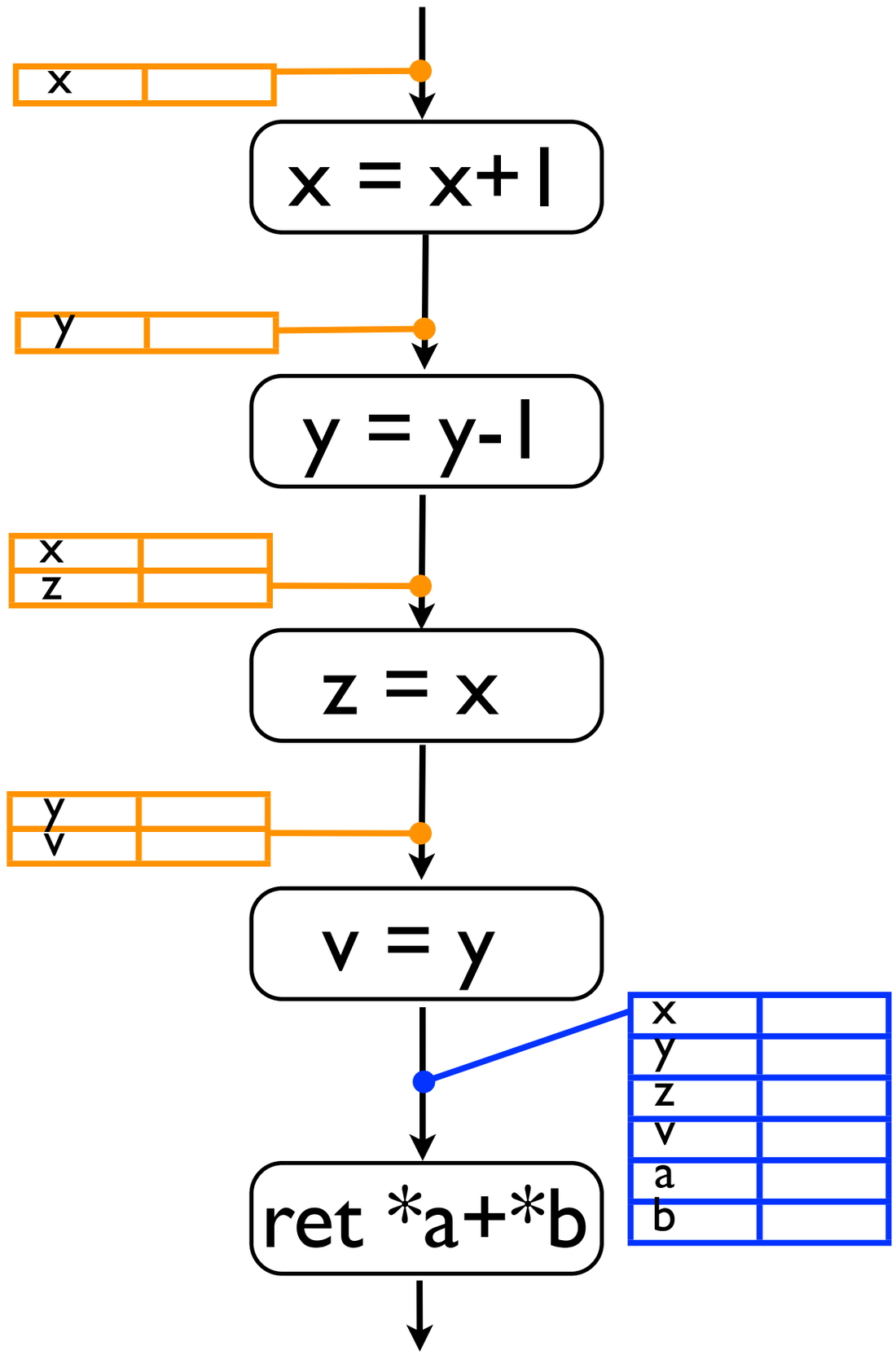

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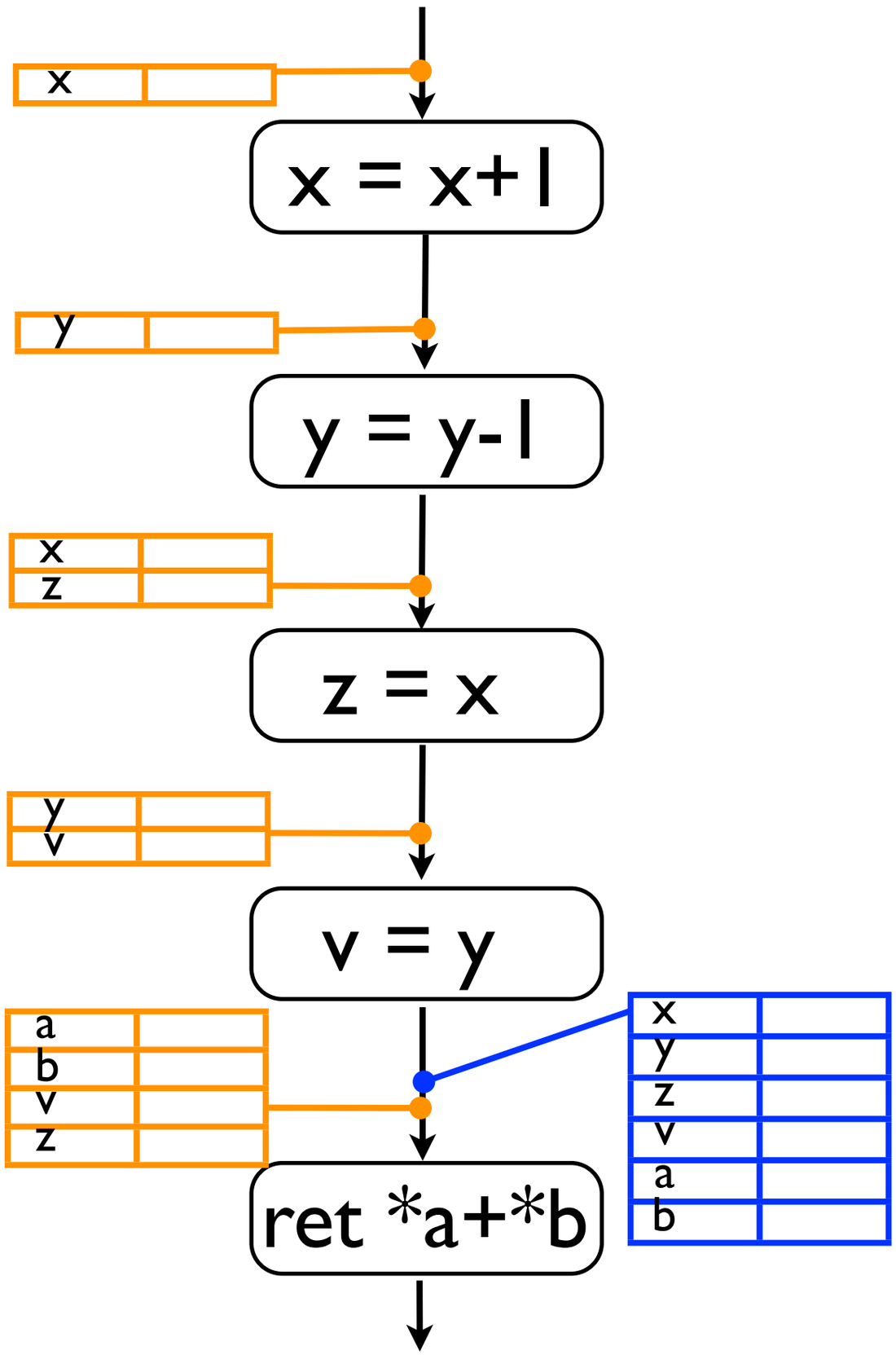

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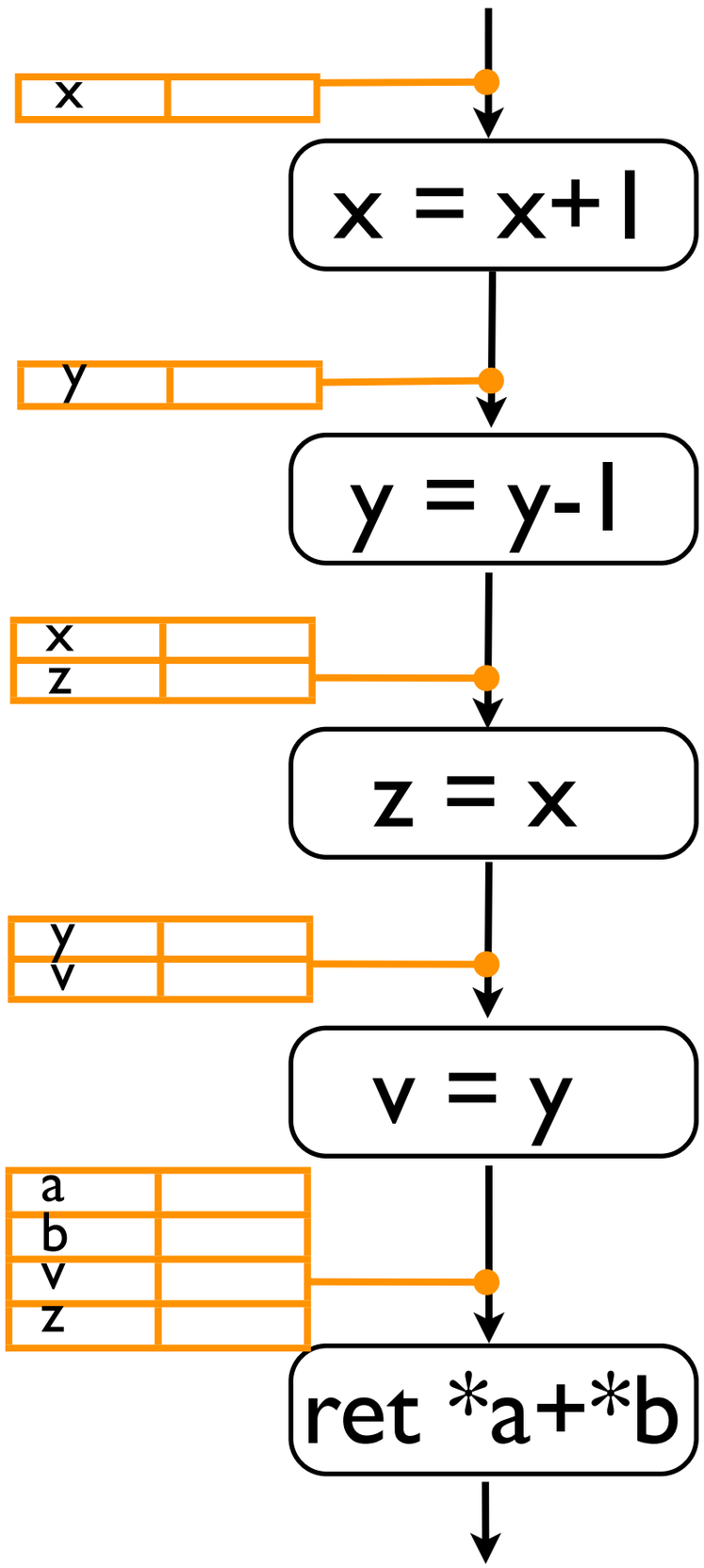

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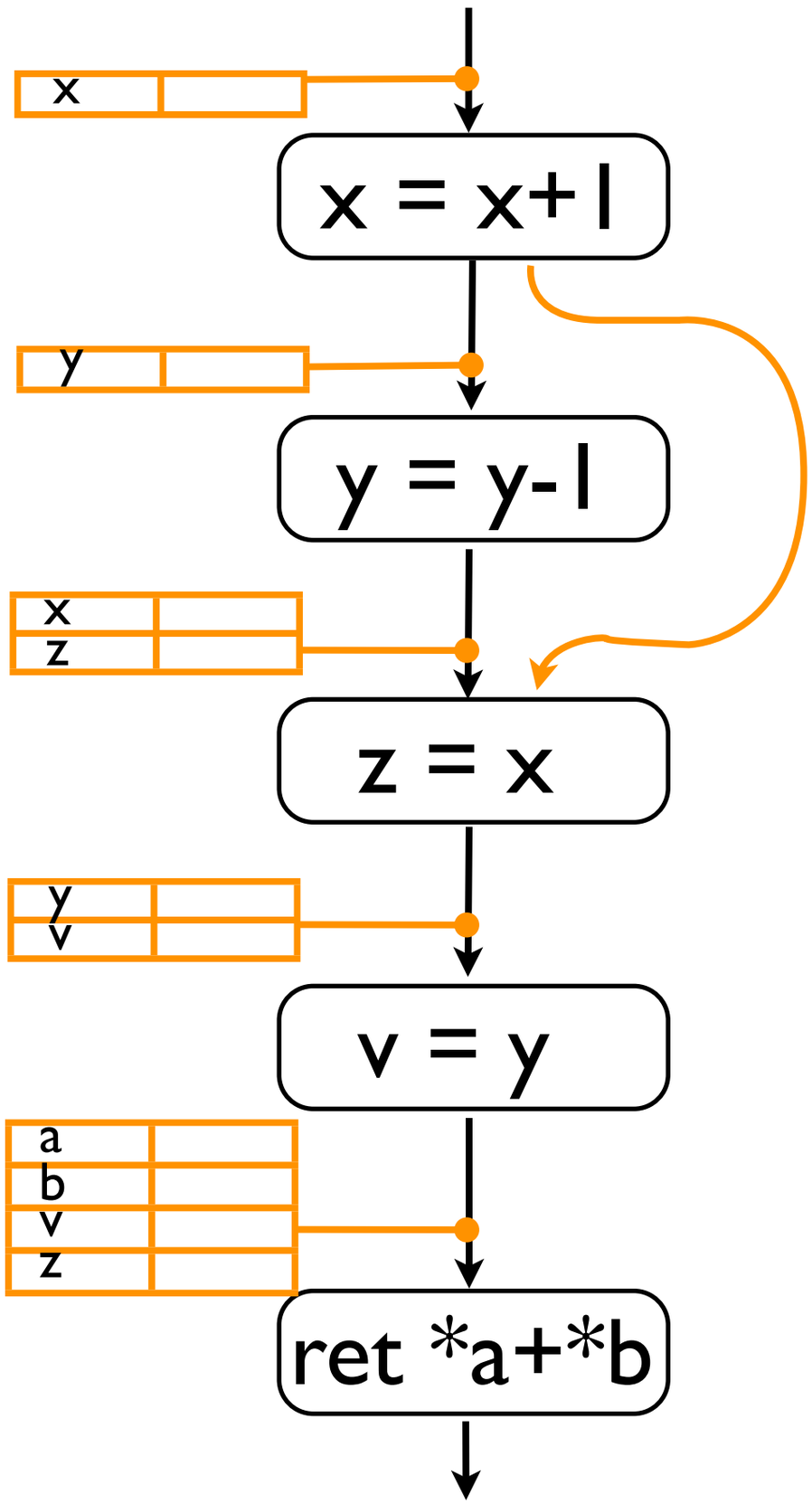

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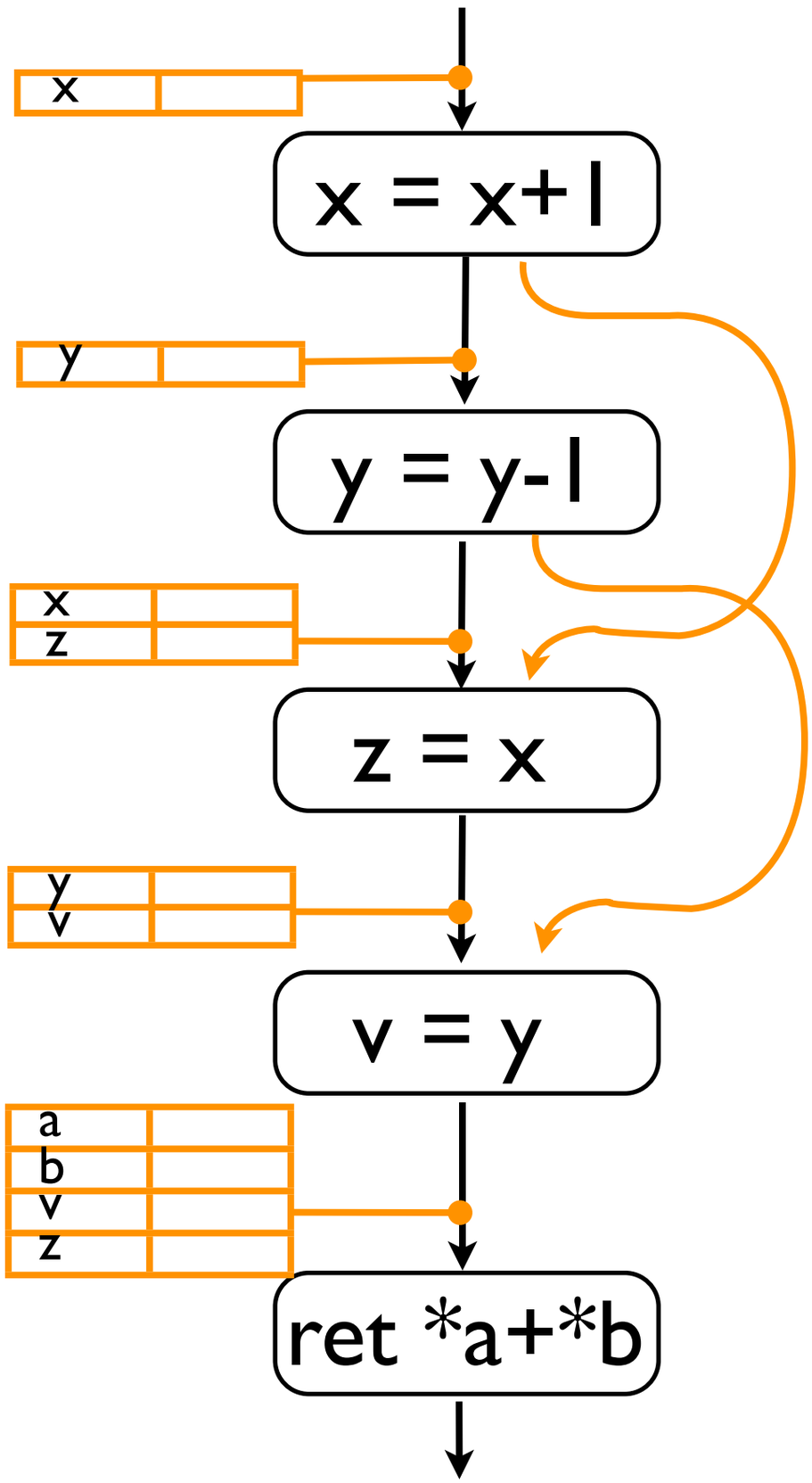

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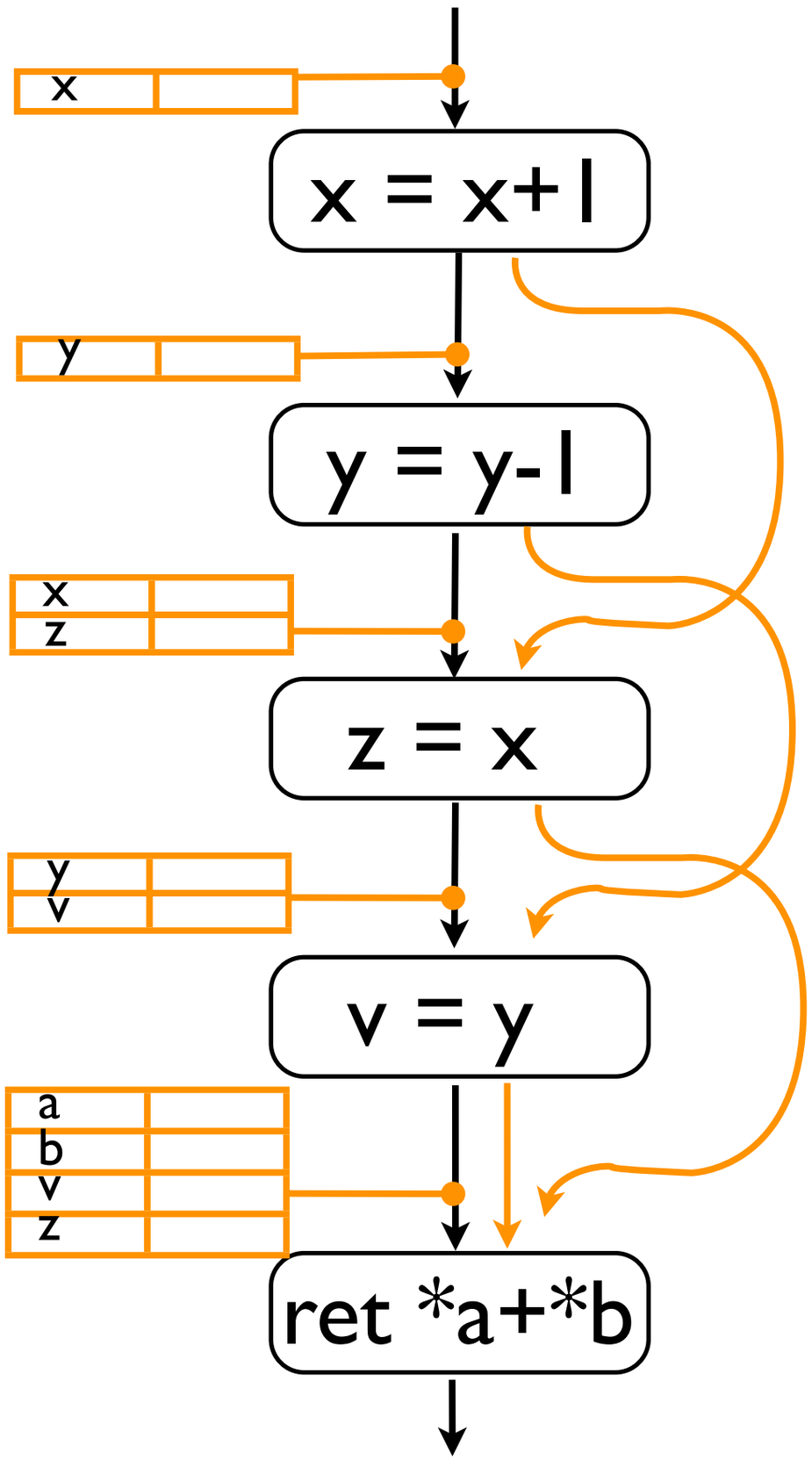
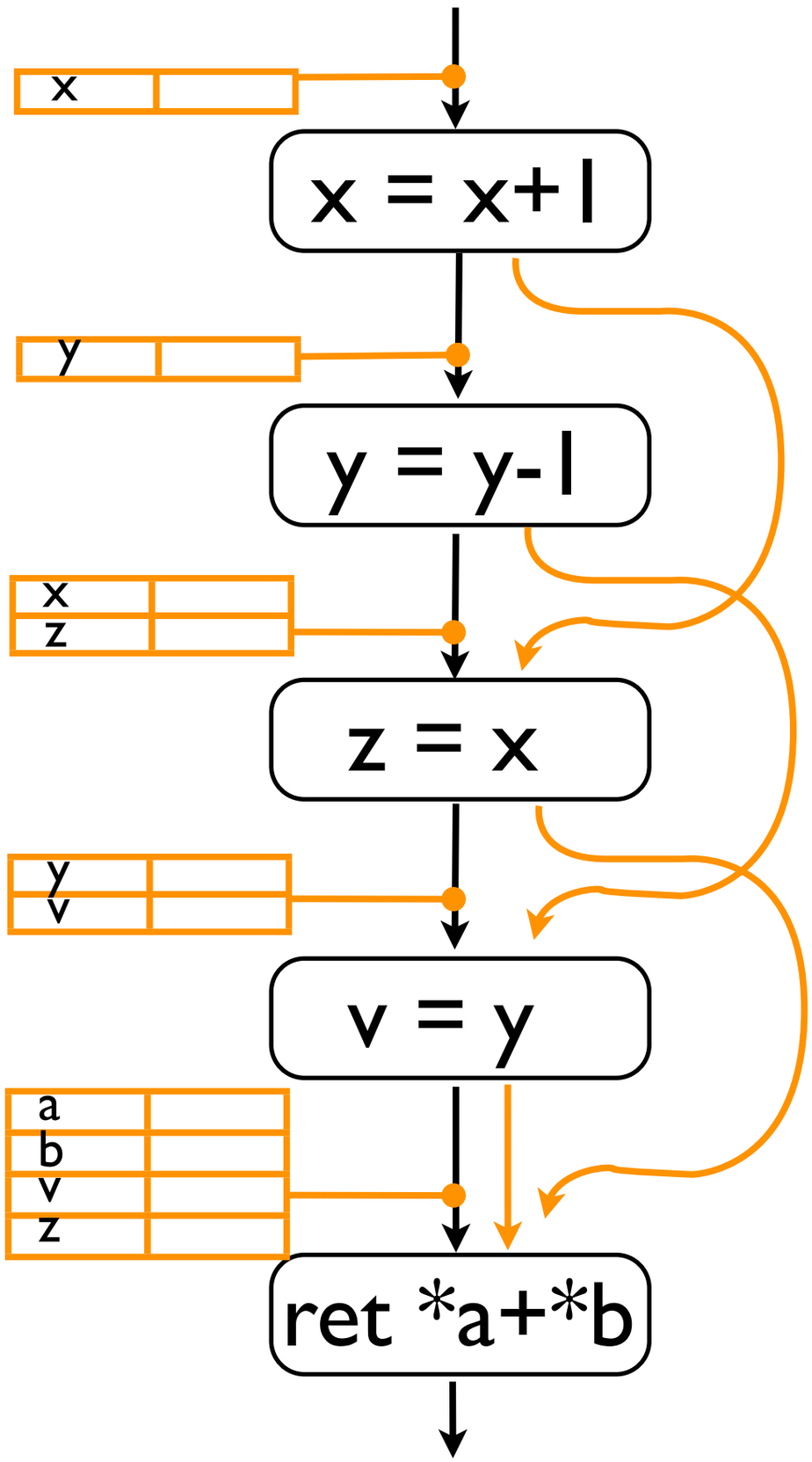


"Sparsifying" the Analysis

"Right Part at Right Moment"

$$\hat{F}(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \hookrightarrow c} \hat{X}(c')).$$

replace syntactic dependency by semantic dependency (data dependency)



Towards Sparse Version

Analyzer computes the fixpoint of $\hat{F}_{\_} \in (\mathbb{C} \to \hat{\mathbb{S}}) \to (\mathbb{C} \to \hat{\mathbb{S}})$

- baseline non-sparse one

$$\hat{F}(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \hookrightarrow c} \hat{X}(c')).$$

- unrealizable sparse version

$$\hat{F}_s(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \overset{l}{\rightsquigarrow} c} \hat{X}(c')|_l).$$

- realizable sparse version

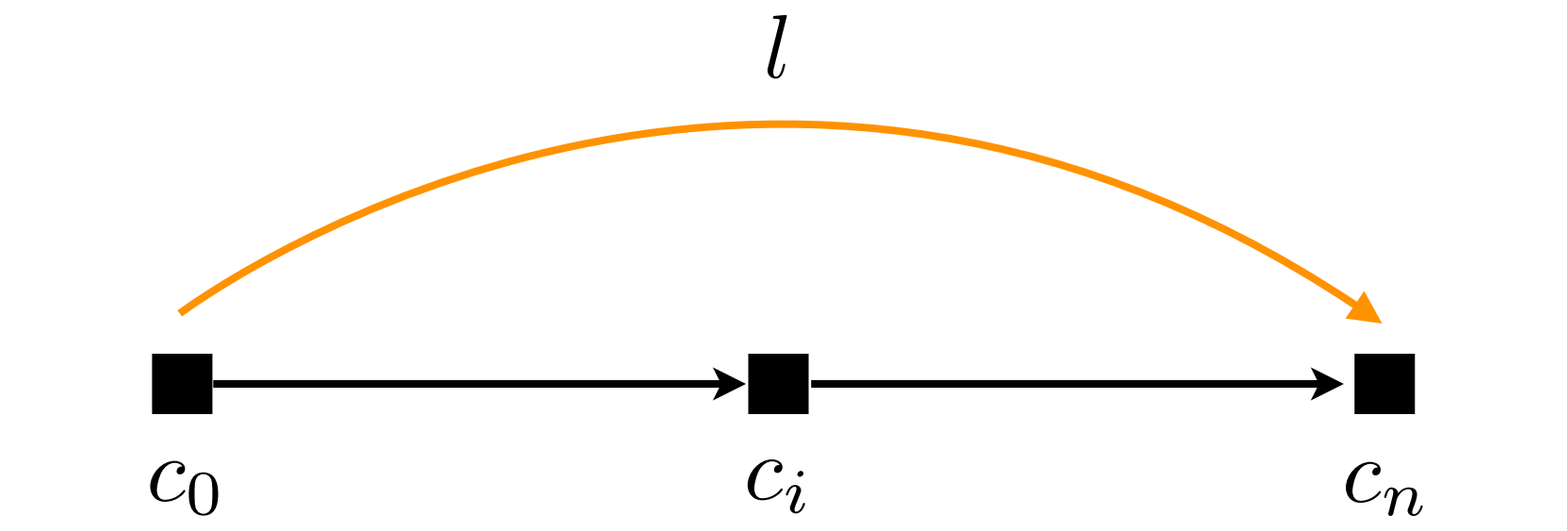
$$\hat{F}_a(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \overset{l}{\rightsquigarrow}_a c} \hat{X}(c')|_l).$$

Unrealizable Sparse One

$$\hat{F}_s(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \overset{l}{\rightsquigarrow} c} \hat{X}(c')|_l).$$

Data Dependency

$$c_0 \overset{l}{\rightsquigarrow} c_n \triangleq \exists c_0 \ldots c_n \in \mathsf{Paths}, l \in \hat{\mathbb{L}}.$$
$$l \in \mathsf{D}(c_0) \cap \mathsf{U}(c_n) \wedge \forall i \in (0,n).l \notin \mathsf{D}(c_i)$$



$l \in \mathsf{D}(c_0)$ $l \notin \mathsf{D}(c_i)$ $l \in \mathsf{U}(c_n)$

Unrealizable Sparse One

$$\hat{F}_s(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \overset{l}{\rightsquigarrow} c} \hat{X}(c')|_l).$$

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Def-Use Sets

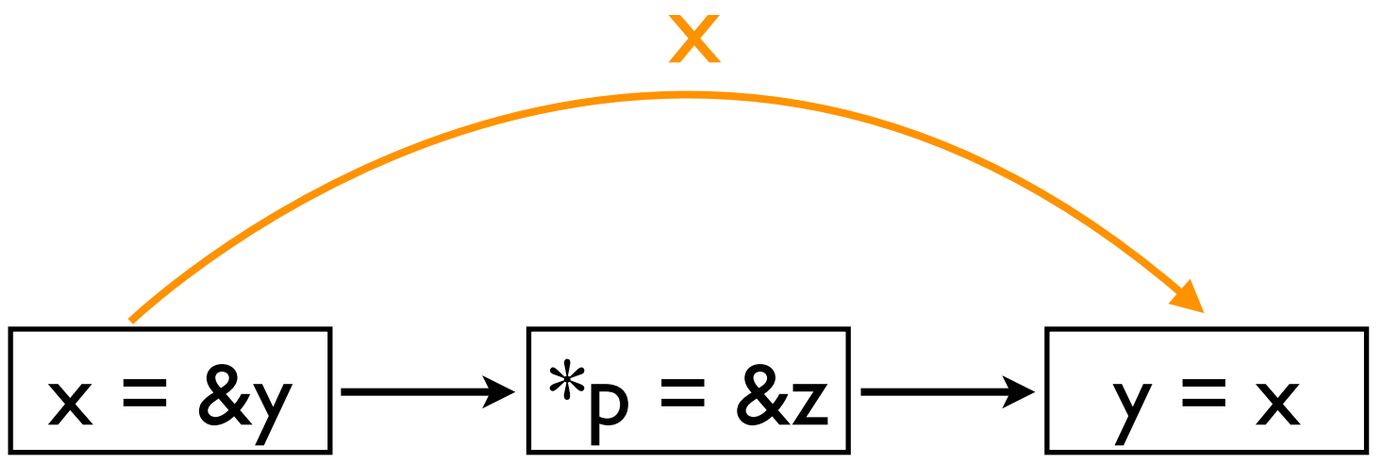
$$\mathsf{D}(c) \triangleq \{l \in \hat{\mathbb{L}} \mid \exists \hat{s} \sqsubseteq \bigsqcup_{c' \hookrightarrow c} (\mathit{fix}\hat{F})(c').\hat{f}_c(\hat{s})(l) \neq \hat{s}(l)\}.$$

$$\mathsf{U}(c) \triangleq \{l \in \hat{\mathbb{L}} \mid \exists \hat{s} \sqsubseteq \bigsqcup_{c' \hookrightarrow c} (\mathit{fix}\hat{F})(c').\hat{f}_c(\hat{s})|_{\mathsf{D}(c)} \neq \hat{f}_c(\hat{s}\backslash_l)|_{\mathsf{D}(c)}\}.$$

Preserving

$$\mathit{fix}\hat{F} = \mathit{fix}\hat{F}_s \quad \text{modulo D}$$

Data Dependency Example



Def	{x}	{a, b}	{y}
Use	ϕ	{p, a, b}	{x}

Realizable Sparse One

$$\hat{F}_a(\hat{X}) = \lambda c \in \mathbb{C}.\hat{f}_c(\bigsqcup_{c' \overset{l}{\rightsquigarrow}_a c} \hat{X}(c')|_l).$$

Realizable Data Dependency

$$c_0 \overset{l}{\rightsquigarrow}_a c_n \triangleq \exists c_0 \ldots c_n \in \mathsf{Paths}, l \in \hat{\mathbb{L}}.$$
$$l \in \mathsf{D}(c_0) \cap \mathsf{U}(c_n) \wedge \forall i \in (0,n).l \notin \mathsf{D}(c_i)$$

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Preserving

$$fix\hat{F} \overset{\text{still}}{=} fix\hat{F}_a \quad \text{modulo } \hat{\mathsf{D}}$$

If the following two conditions hold

Conditions of $\hat{\mathsf{D}}$ & $\hat{\mathsf{U}}$

- over-approximation

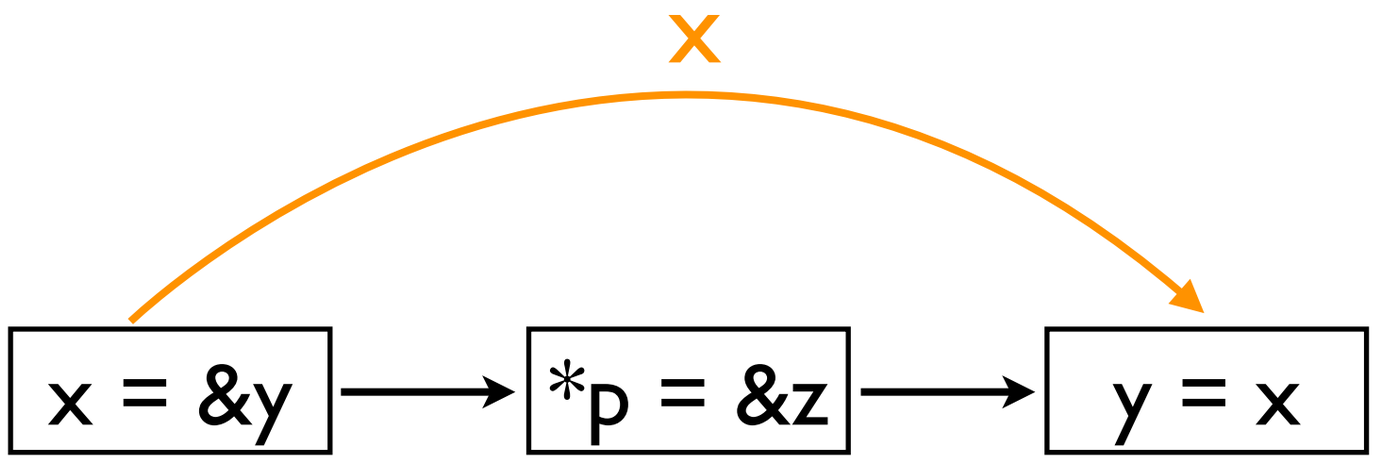
$$\mathsf{D}(c) \supseteq \mathsf{D}(c) \wedge \mathsf{U}(c) \supseteq \mathsf{U}(c)$$

- spurious definitions should be also included in uses

$$\underline{\hat{\mathsf{D}}(c) - \mathsf{D}(c)} \subseteq \hat{\mathsf{U}}(c)$$

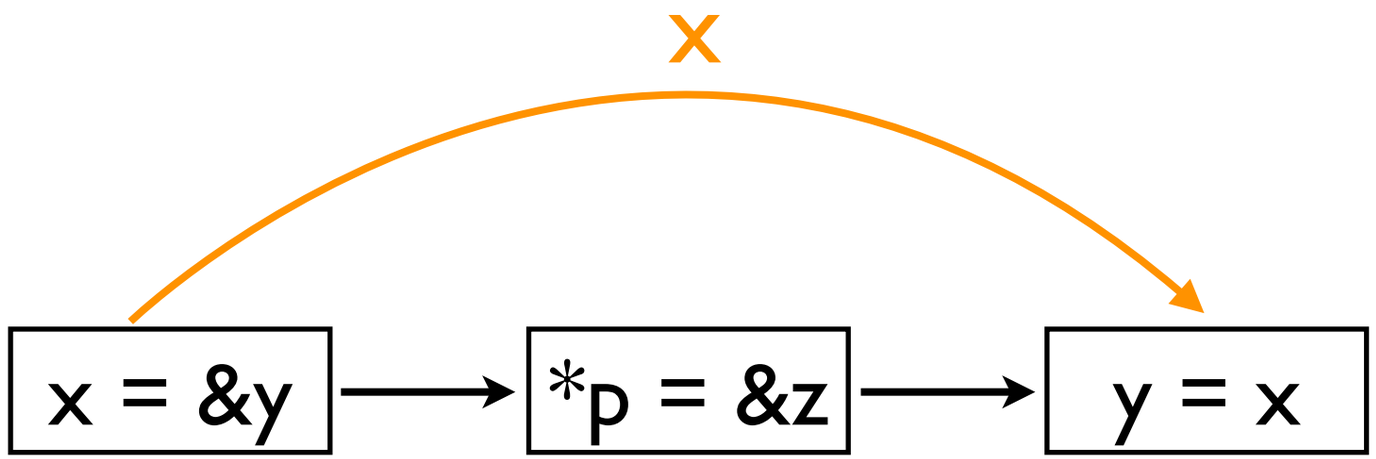
spurious definitions

Why the Conditions of $\hat{D}$ & $\hat{U}$



Def	{x}	{a, b}	{y}
Use	ϕ	{p, a, b}	{x}

Why the Conditions of $\hat{D}$ & $\hat{U}$

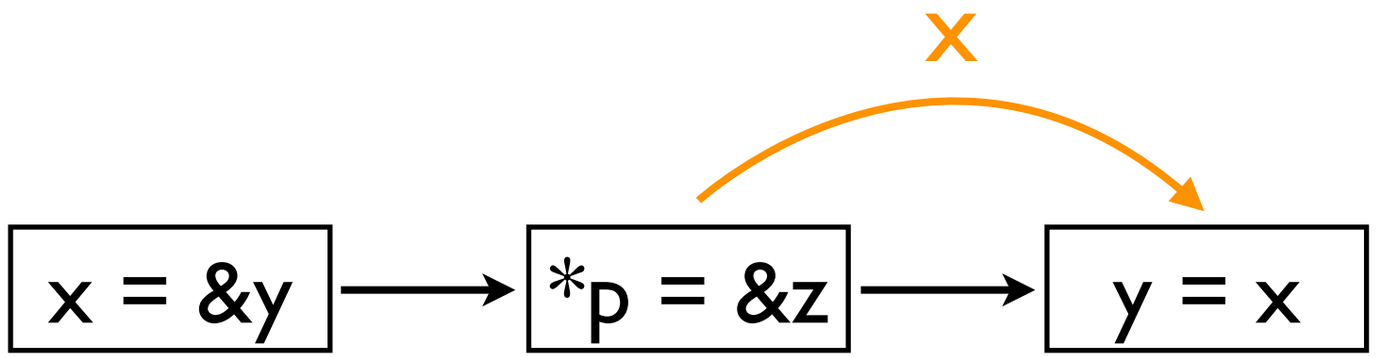


Approx. Def	{x}	{a, b, x}	{y}
Approx. Use	ϕ	{p, a, b}	{x}

$$\underline{\hat{D}(c) - D(c)} \not\subseteq \hat{U}(c)$$

{x}

Why the Conditions of $\hat{D}$ & $\hat{U}$



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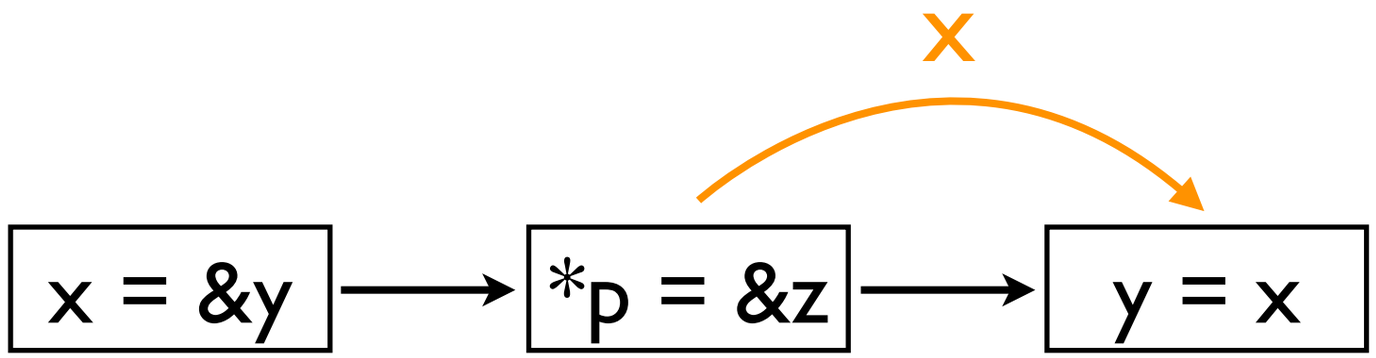
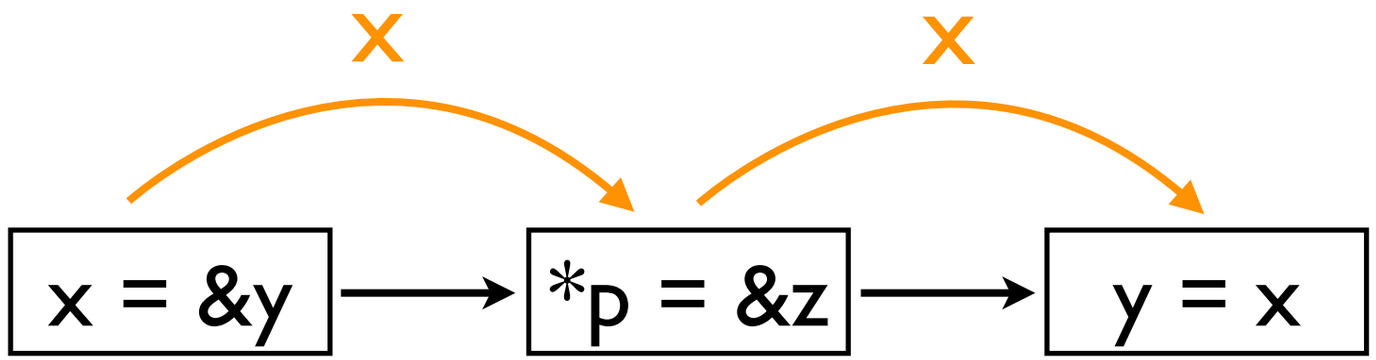


Approx. Def	{x}	{a, b, x}	{y}
Approx. Use	ϕ	{p, a, b, x}	{x}

$$\frac{\hat{D}(c) - D(c) \subseteq \hat{U}(c)}{\{x\}}$$

Why the Conditions of $\hat{D}$ & $\hat{U}$



Approx. Def	{x}	{a, b, x}	{y}
Approx. Use	ϕ	{p, a, b, x}	{x}

$$\frac{\hat{D}(c) - D(c) \subseteq \hat{U}(c)}{\{x\}}$$

Hurdle: $\hat{D}$ & $\hat{U}$ Before Analysis?

- Yes, by yet another analysis with further abstraction
  - e.g., flow-insensitive abstraction

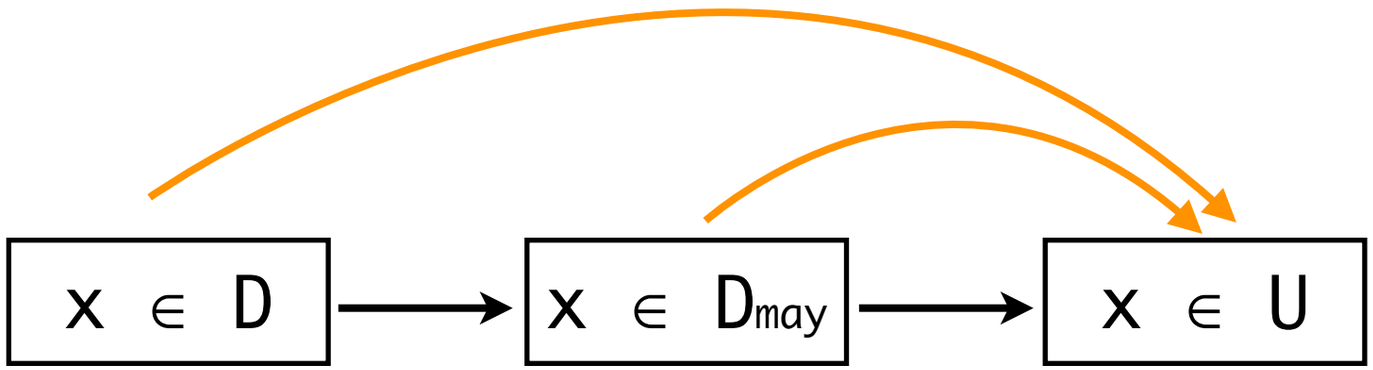
$$\mathbb{C} \to \hat{\mathbb{S}} \underset{\alpha}{\overset{\gamma}{\leftrightarrows}} \hat{\mathbb{S}} \qquad \hat{F}_p = \lambda \hat{s}.(\bigsqcup_{c \in \mathbb{C}} \hat{f}_c(\hat{s}))$$

- In implementation, $\hat{U}$ includes $\hat{D}$

$$\hat{\mathsf{D}}(c) - \mathsf{D}(c) \subseteq \hat{\mathsf{U}}(c)$$

Existing Sparse Techniques
(developed mostly in dfa community)

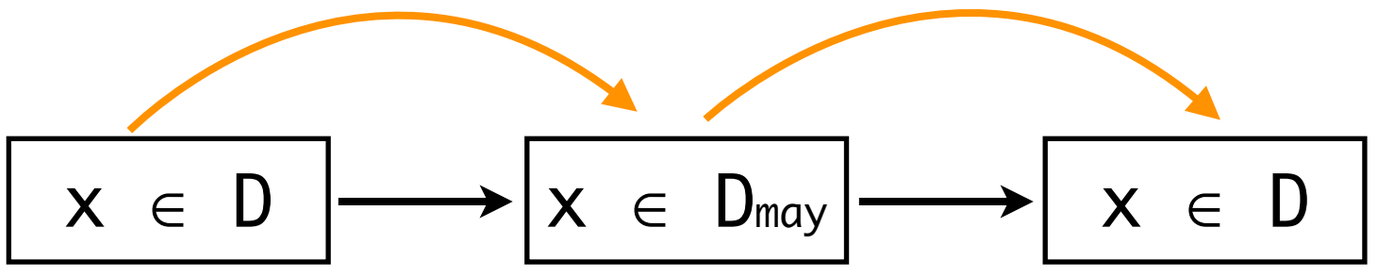
- Different notion of data dependency



def-use chains fail to preserve original precision

Existing Sparse Techniques
(developed mostly in dfa community)

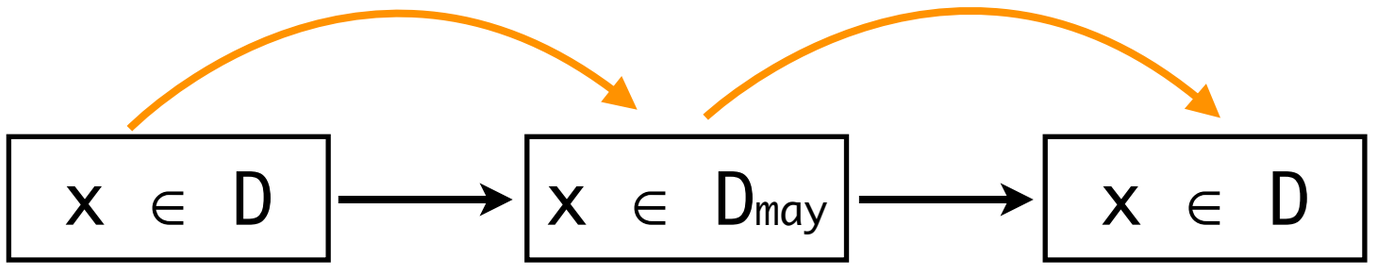
- Different notion of data dependency



our data dependency preserves original precision

Existing Sparse Techniques
(developed mostly in dfa community)

- Different notion of data dependency



- Existing sparse analyses are not general
  - tightly coupled with particular analysis, or
  - limited to a particular target language

Performance

Experiments

- On top of Sparrow The Early Bird
  - Sparse non-relational analysis with interval domain

$$\hat{\mathbb{S}} = AbsLoc \rightarrow Interval$$

- Sparse relational analysis with octagon domain

$$\hat{\mathbb{S}} = Packs \rightarrow Octagon$$

Performance

Sparse Interval Analysis

Program	**LOC**	**Non-sparse**		**Sparse**		**Spd↑**	**Mem↓**
		Time	**Mem**	**Time**	**Mem**		
gzip-1.2.4a	7 K	772	240	3	63	257 x	74 %
bc-1.06	13 K	1,270	276	7	75	181 x	73 %
less-382	23 K	9,561	1,113	33	127	289 x	86 %
make-3.76.1	27 K	24,240	1,391	21	114	1,154 x	92 %
wget-1.9	35 K	44,092	2,546	11	85	4,008 x	97 %
a2ps-4.14	64 K	∞	N/A	40	353	N/A	N/A
sendmail-8.13.6	130 K	∞	N/A	744	678	N/A	N/A
nethack-3.3.0	211 K	∞	N/A	16,373	5,298	N/A	N/A
emacs-22.1	399 K	∞	N/A	37,830	7,795	N/A	N/A
python-2.5.1	435 K	∞	N/A	11,039	5,535	N/A	N/A
linux-3.0	710 K	∞	N/A	33,618	20,529	N/A	N/A
gimp-2.6	959 K	∞	N/A	3,874	3,602	N/A	N/A
ghostscript-9.00	1,363 K	∞	N/A	14,814	6,384	N/A	N/A

Performance

Sparse Interval Analysis

Program	LOC	Non-sparse		Sparse		Spd↑	Mem↓
		Time	Mem	Time	Mem		
gzip-1.2.4a	7 K	772	240	3	63	257 x	74 %
bc-1.06	13 K	1,270	276	7	75	181 x	73 %
less-382	23 K	9,561	1,113	33	127	289 x	86 %
make-3.76.1	27 K	24,240	1,391	21	114	1,154 x	92 %
wget-1.9	35 K	44,092	2,546	11	85	4,008 x	97 %
a2ps-4.14	64 K	∞	N/A	40	353	N/A	N/A
sendmail-8.13.6	130 K	∞	N/A	744	678	N/A	N/A
nethack-3.3.0	211 K	∞	N/A	16,373	5,298	N/A	N/A
emacs-22.1	399 K	∞	N/A	37,830	7,795	N/A	N/A
python-2.5.1	435 K	∞	N/A	11,039	5,535	N/A	N/A
linux-3.0	710 K	∞	N/A	33,618	20,529	N/A	N/A
gimp-2.6	959 K	∞	N/A	3,874	3,602	N/A	N/A
ghostscript-9.00	1,363 K	∞	N/A	14,814	6,384	N/A	N/A

Performance

Sparse Octagon Analysis

Program	**LOC**	**Non-sparse**		**Sparse**		**Spd↑**	**Mem↓**
		Time	**Mem**	**Time**	**Mem**		
gzip-1.2.4a	7 K	2,078	2,832	21	269	98 x	91 %
bc-1.06	13 K	9,536	6,987	55	358	173 x	95 %
tar-1.13	20 K	∞	N/A	188	526	N/A	N/A
less-382	23 K	∞	N/A	432	458	N/A	N/A
make-3.76.1	27 K	∞	N/A	331	666	N/A	N/A
wget-1.9	35 K	∞	N/A	288	646	N/A	N/A
screen-4.0.2	45 K	∞	N/A	16,433	9,199	N/A	N/A
a2ps-4.14	64 K	∞	N/A	8,546	1,996	N/A	N/A
sendmail-8.13.6	130 K	∞	N/A	64,808	29,658	N/A	N/A

Summary

Our Sparse Framework

For precise, sound, and scalable static analysis

- Define a global safe abstract interpreter
- Make it sparse with our data dependencies
- Resulting sparse one scales with the same precision

Thank you