20th International Workshop on Termination

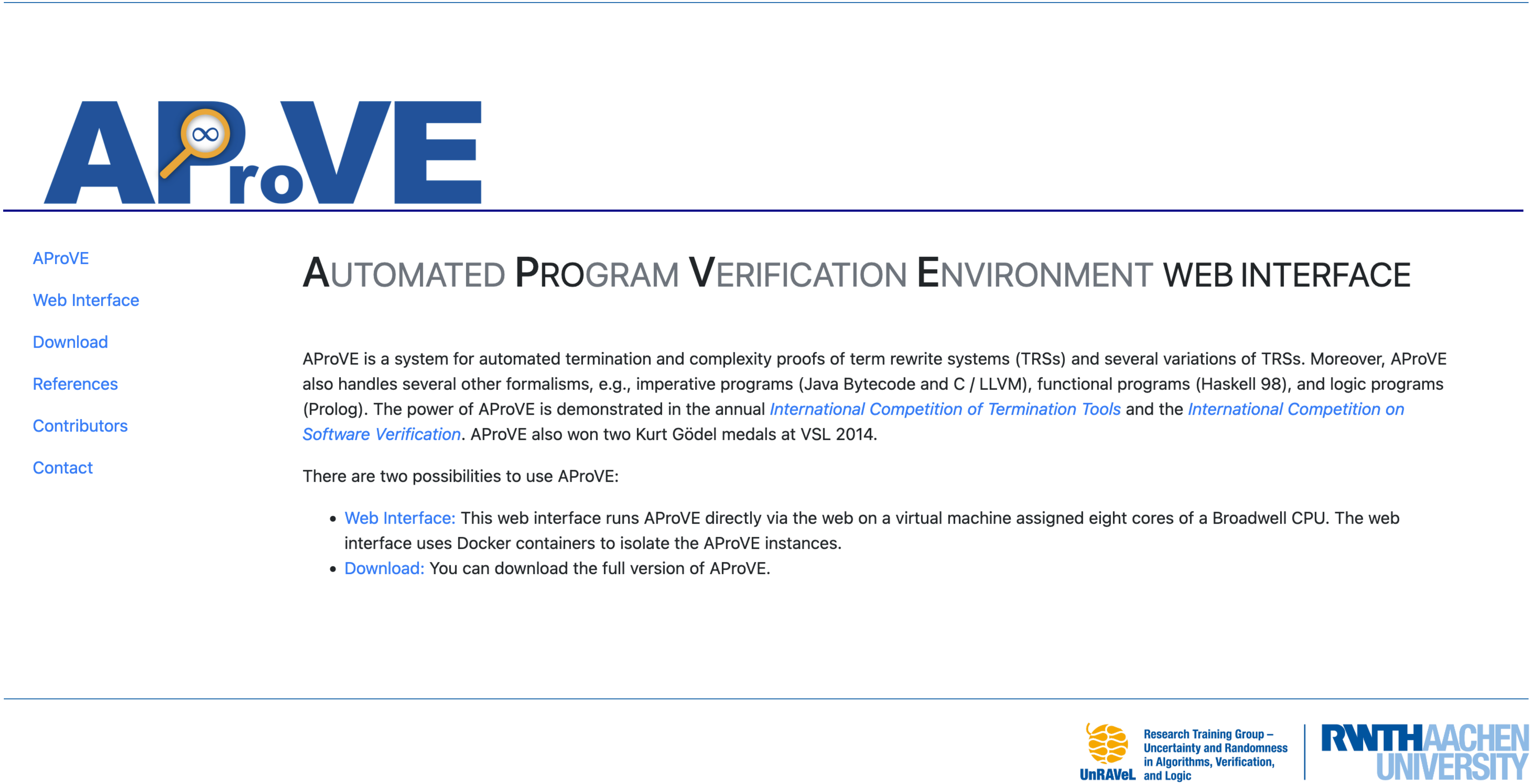
Florian Frohn, Carsten Fuhs, Jürgen Giesl, **Jan-Christoph Kassing** and Nils Lommen

04.09.2025

AProVE: Becoming Open Source and Recent Improvements

UnRAVeL Research Training Group – Uncertainty and Randomness in Algorithms, Verification, and Logic

RWTH AACHEN UNIVERSITY



AUTOMATED PROGRAM VERIFICATION ENVIRONMENT WEB INTERFACE

AProVE is a system for automated termination and complexity proofs of term rewrite systems (TRSs) and several variations of TRSs. Moreover, AProVE also handles several other formalisms, e.g., imperative programs (Java Bytecode and C / LLVM), functional programs (Haskell 98), and logic programs (Prolog). The power of AProVE is demonstrated in the annual *International Competition of Termination Tools* and the *International Competition on Software Verification*. AProVE also won two Kurt Gödel medals at VSL 2014.

There are two possibilities to use AProVE:

- Web Interface: This web interface runs AProVE directly via the web on a virtual machine assigned eight cores of a Broadwell CPU. The web interface uses Docker containers to isolate the AProVE instances.
- Download: You can download the full version of AProVE.

UnRAVeL
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AProVE

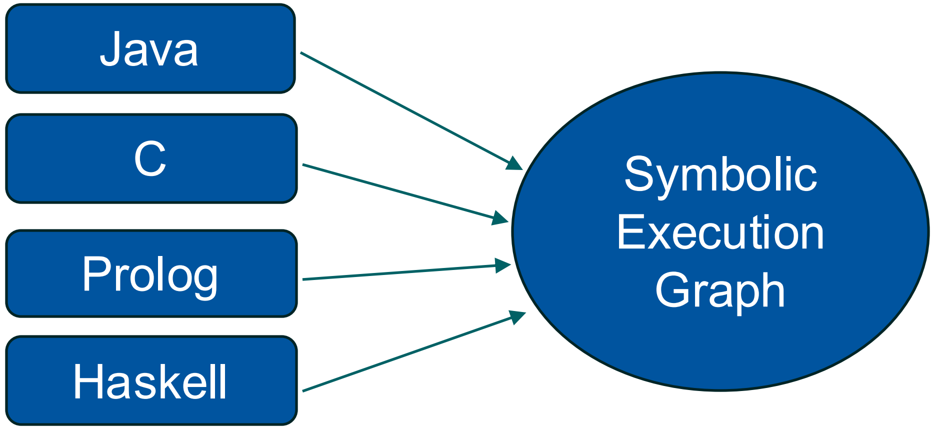
Java

C

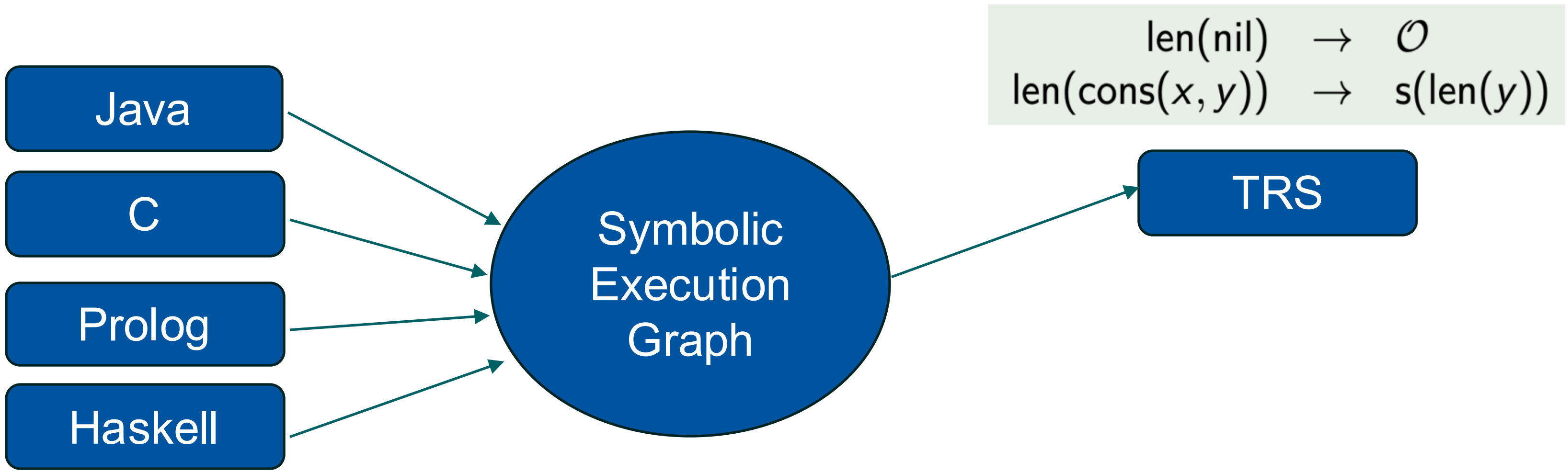
Prolog

Haskell

AProVE

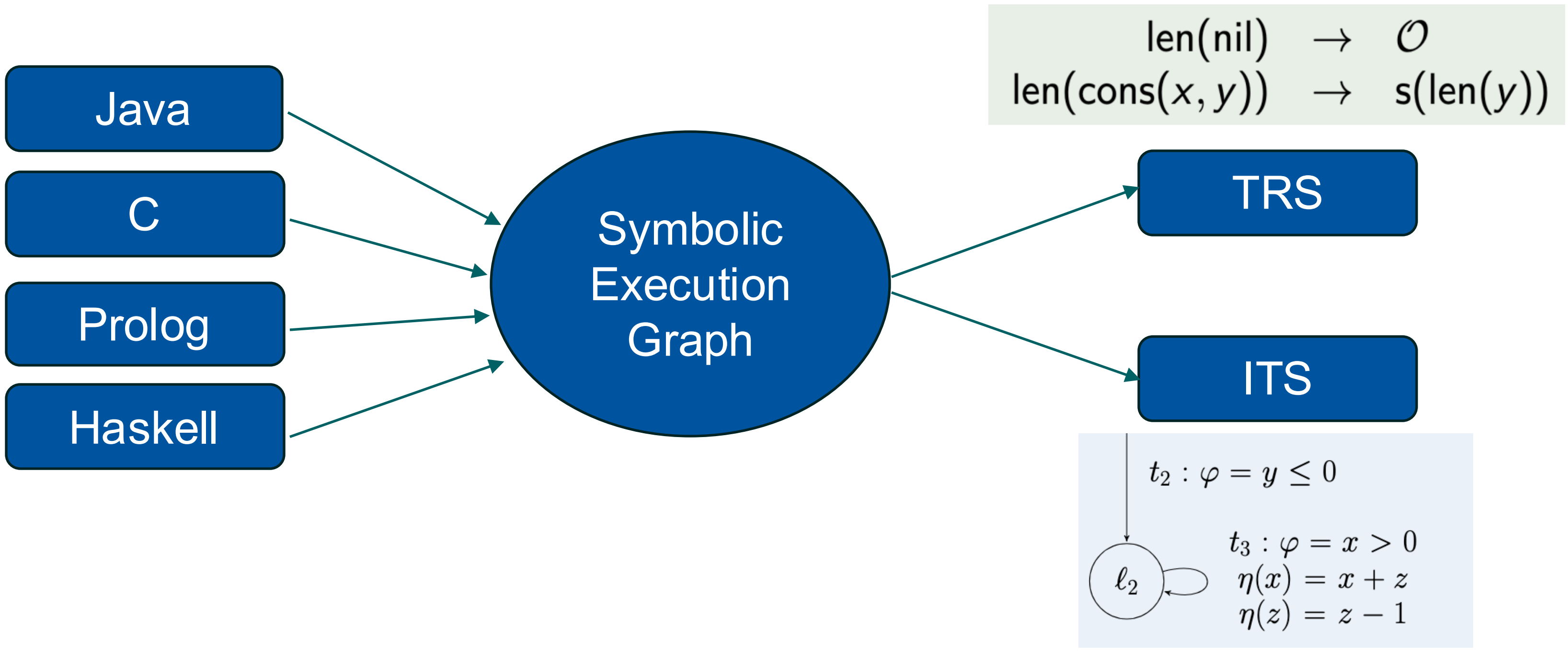


AProVE



$$\begin{aligned} \mathsf{len}(\mathsf{nil}) &\to \mathcal{O} \\ \mathsf{len}(\mathsf{cons}(x, y)) &\to \mathsf{s}(\mathsf{len}(y)) \end{aligned}$$

AProVE



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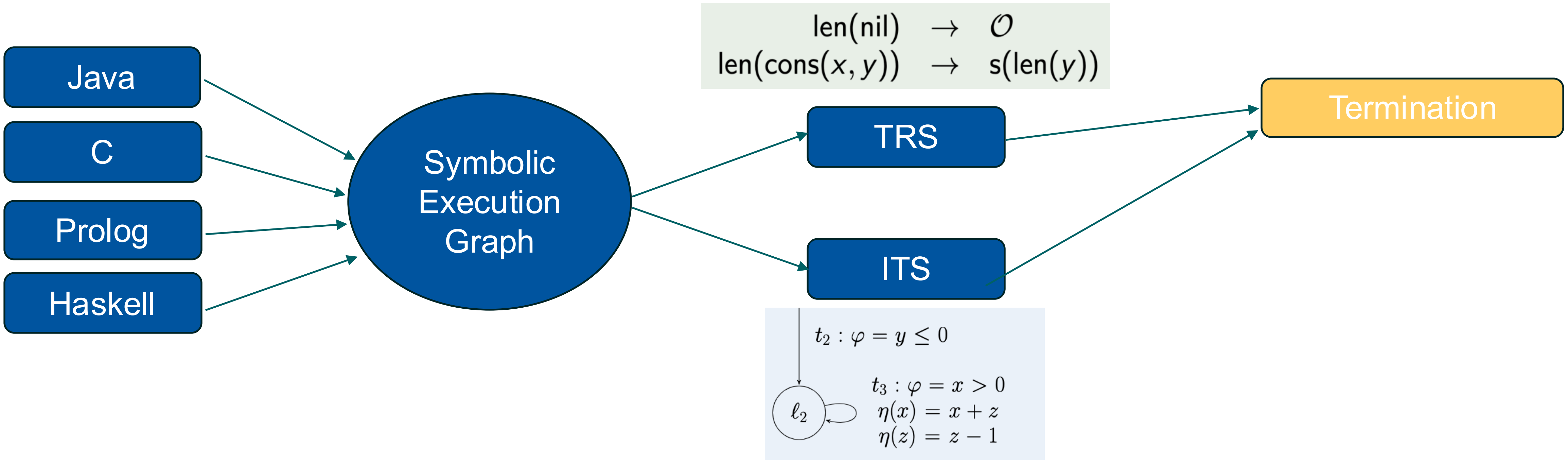


Java

C

Prolog

Haskell

Symbolic Execution Graph

$$\begin{aligned} \mathsf{len}(\mathsf{nil}) &\to \mathcal{O} \\ \mathsf{len}(\mathsf{cons}(x, y)) &\to \mathsf{s}(\mathsf{len}(y)) \end{aligned}$$

TRS

ITS

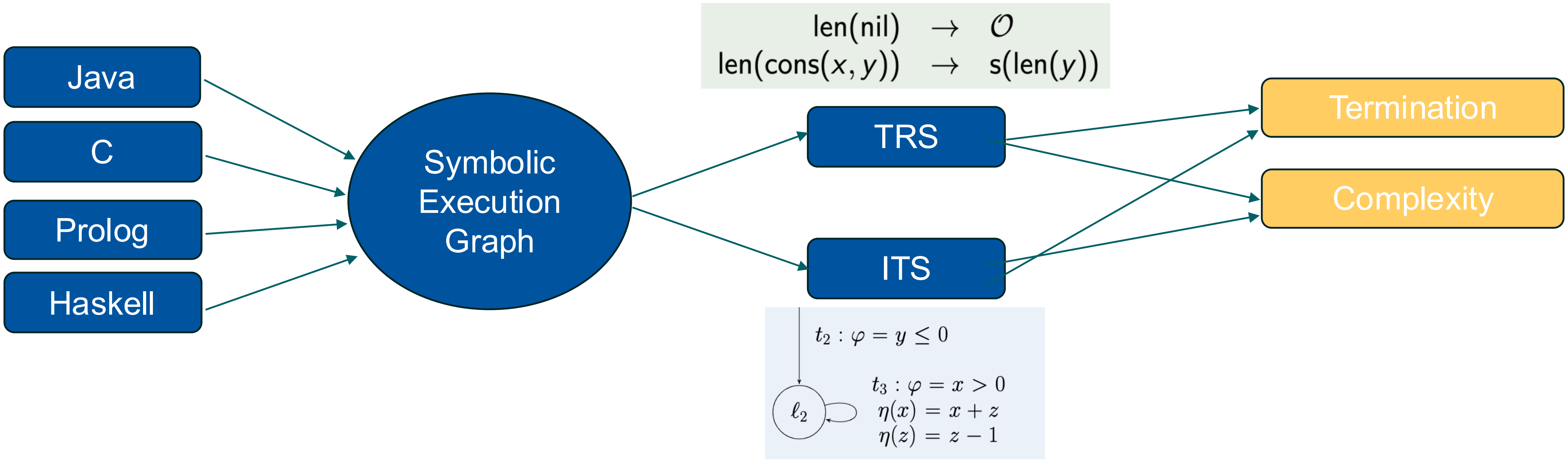
$t_2 : \varphi = y \leq 0$

ℓ_2

$$\begin{aligned} t_3 : \varphi &= x > 0 \\ \eta(x) &= x + z \\ \eta(z) &= z - 1 \end{aligned}$$

Termination

AProVE



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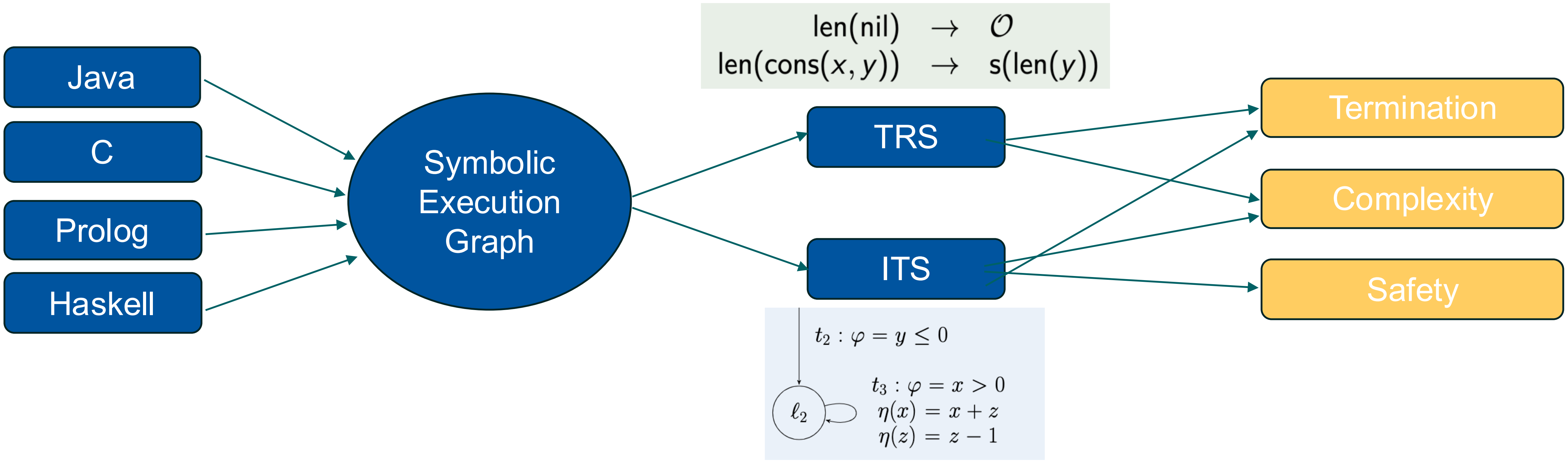
Termination

Complexity

AProVE



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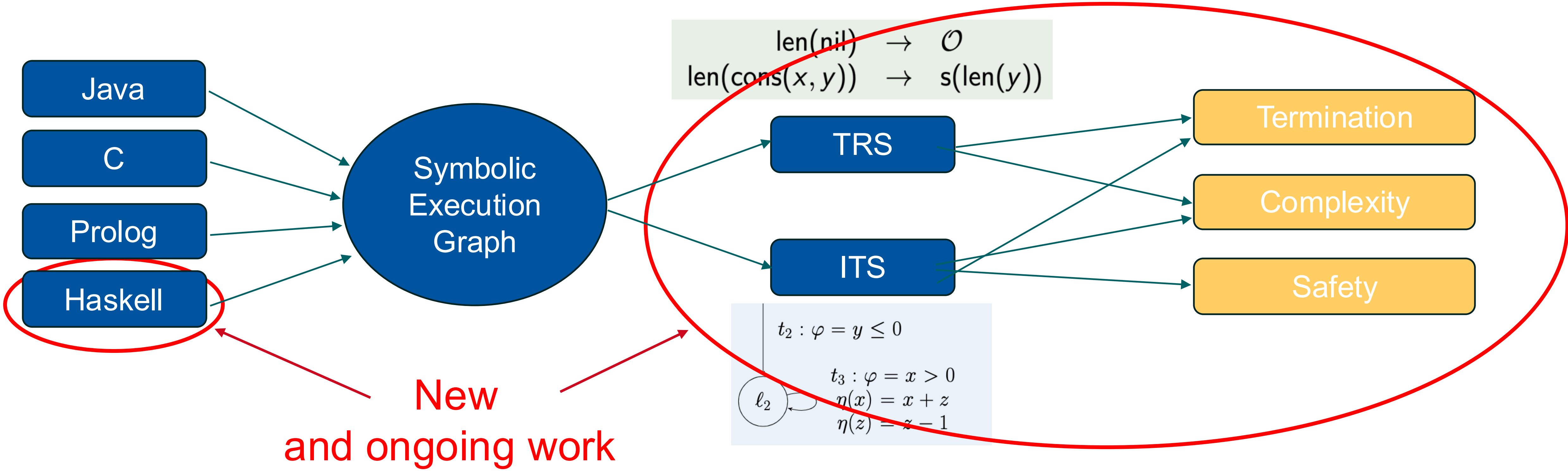

Java

C

Prolog

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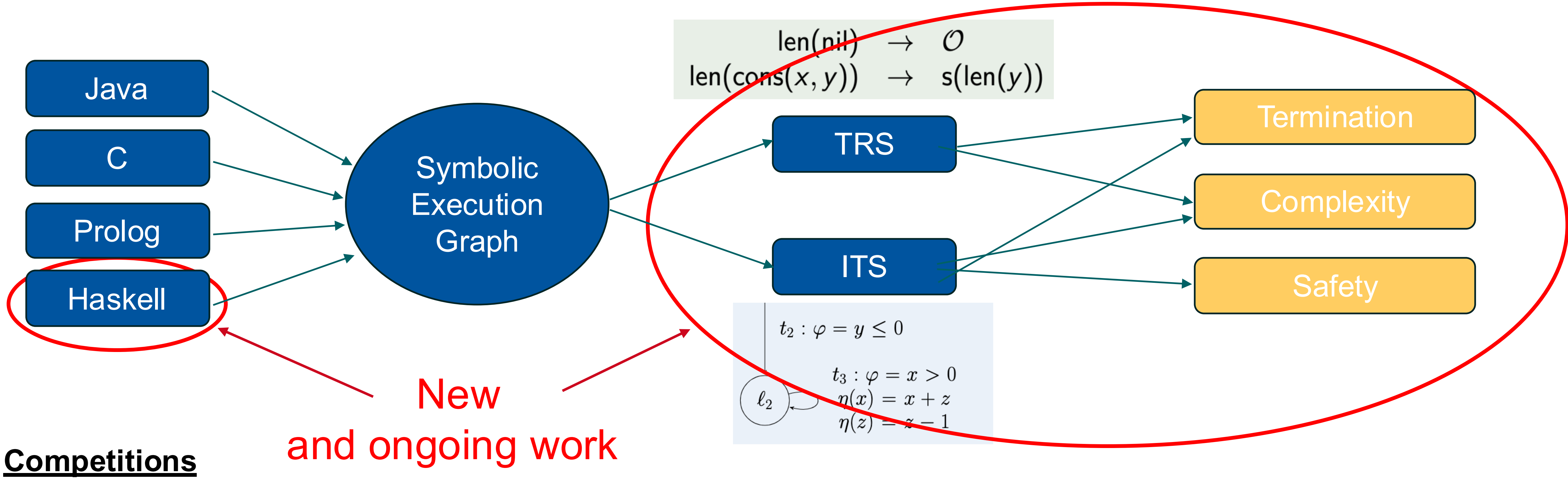
Termination

Complexity

Safety

New
and ongoing work

AProVE



$$
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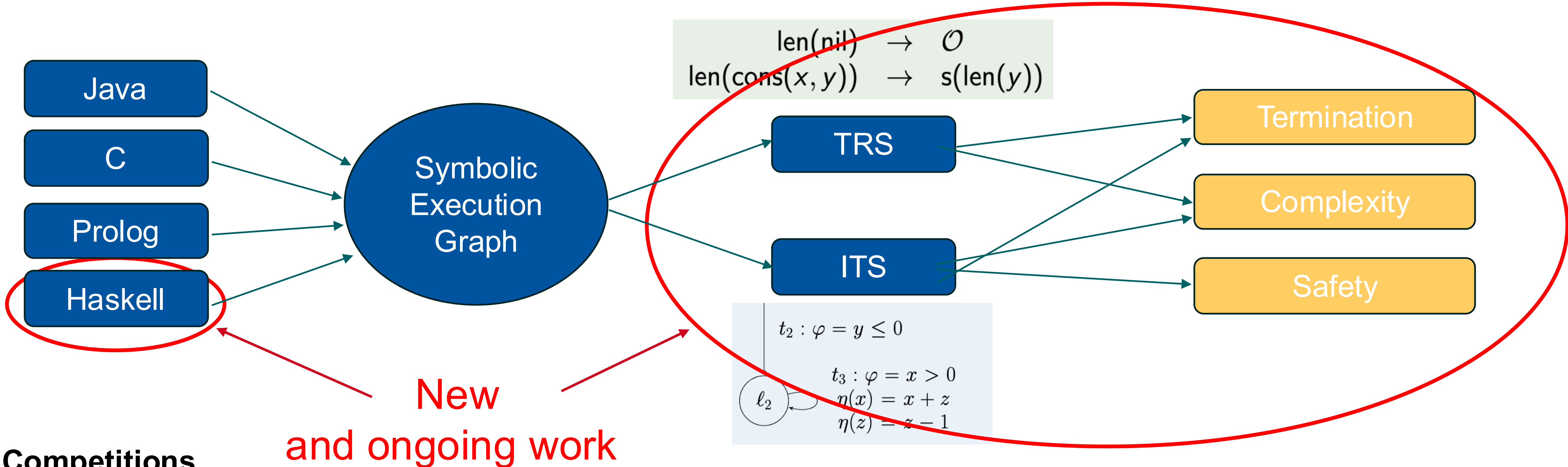
\end{aligned}
$$

New
and ongoing work

Competitions

- Termination Competition
  - Participation in nearly all categories (TRS-Standard, TRS-Relative, Java, C, PTRS-Standard, ITS, etc.)

AProVE



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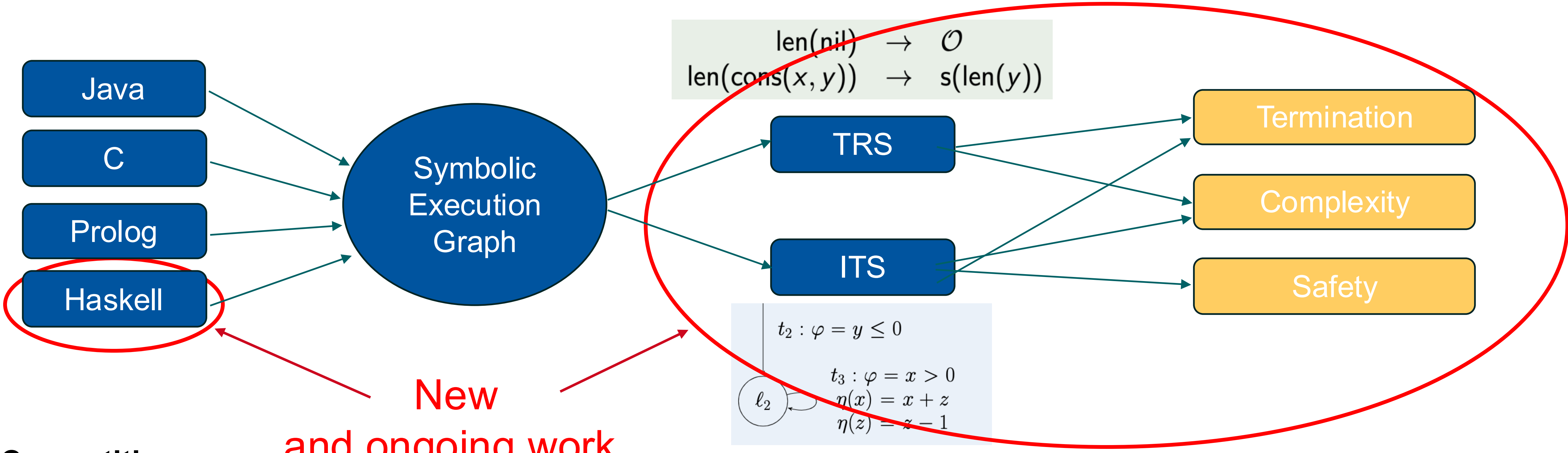
- SV-Comp
  - Participation in termination category of C programs (1. Proton, 2. Ultimate Automizer, **3. AProVE (KoAT & LoAT)**)

AProVE



New
and ongoing work

Competitions

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- SV-Comp
  - Participation in termination category of C programs (1. Proton, 2. Ultimate Automizer, **3. AProVE (KoAT & LoAT)**)
- Confluence Competition (First Time!)
  - Participation in the TRS category for confluence analysis.

Complexity of TRSs

$$\begin{aligned} \mathsf{plus}(\mathcal{O}, y) &\to y \\ \mathsf{plus}(\mathsf{s}(x), y) &\to \mathsf{s}(\mathsf{plus}(x, y)) \end{aligned}$$

Derivational Complexity

Runtime Complexity

Complexity of TRSs

$$\begin{array}{rcl} \mathsf{plus}(\mathcal{O}, y) & \to & y \\ \mathsf{plus}(\mathsf{s}(x), y) & \to & \mathsf{s}(\mathsf{plus}(x, y)) \end{array}$$

$$\mathsf{f}(c_1, \ldots, c_n)$$

Derivational Complexity

Runtime Complexity

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$\mathsf{plus}(\mathsf{s}(0), \mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0)))$

Derivational Complexity

$\mathsf{f}(c_1, \ldots, c_n)$ $\mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0))$

Runtime Complexity

Complexity of TRSs

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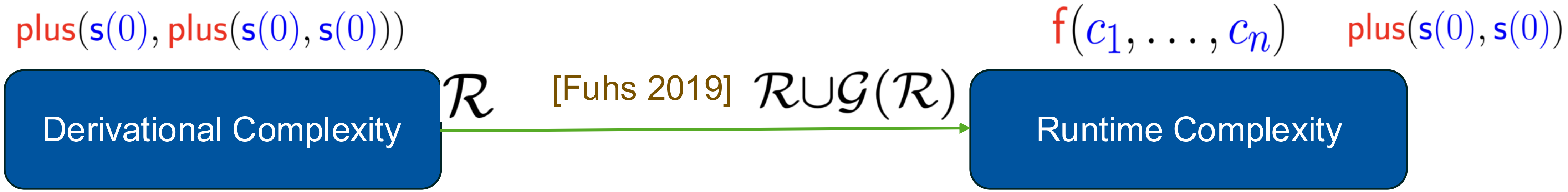

$\mathsf{plus}(\mathsf{s}(0), \mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0)))$

$\mathsf{f}(c_1, \ldots, c_n)$ $\quad$ $\mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0))$

$\mathcal{R}$ [Fuhs 2019] $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Complexity of TRSs

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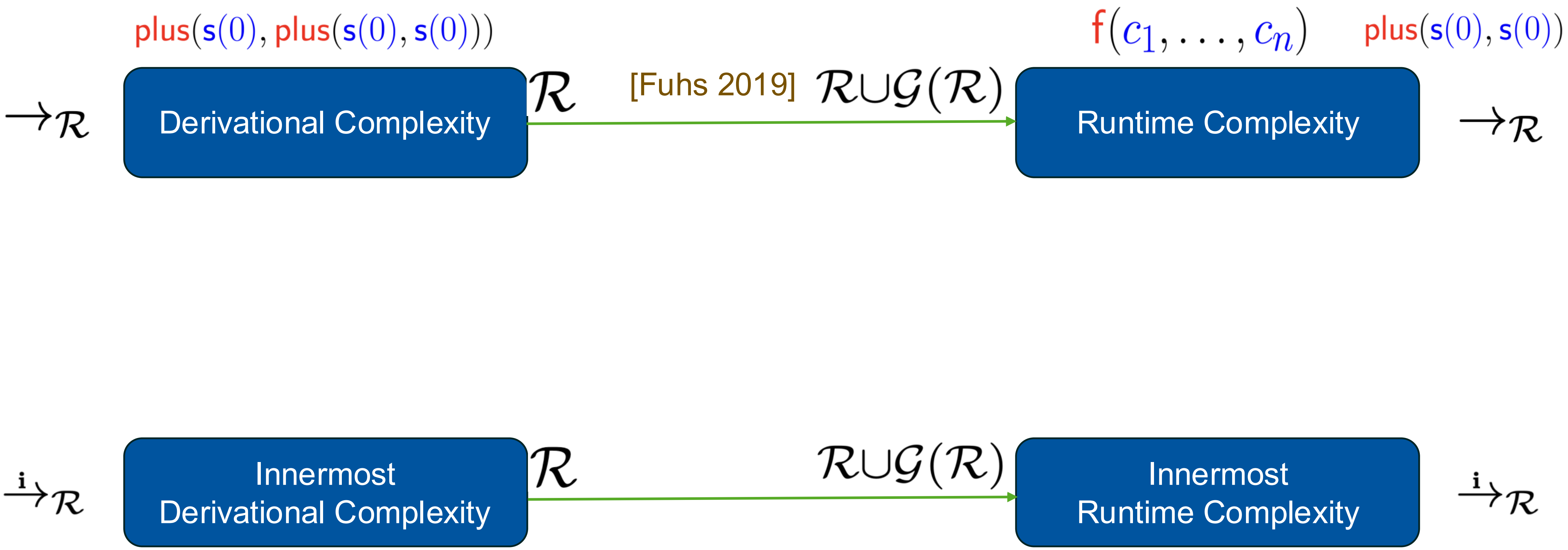

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$\mathsf{f}(c_1, \ldots, c_n)$

$\mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0))$

$\to_{\mathcal{R}}$ Derivational Complexity $\mathcal{R}$ [Fuhs 2019] $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$ Runtime Complexity $\to_{\mathcal{R}}$

$\xrightarrow{\mathbf{i}}_{\mathcal{R}}$ Innermost Derivational Complexity $\mathcal{R}$ $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$ Innermost Runtime Complexity $\xrightarrow{\mathbf{i}}_{\mathcal{R}}$

Complexity of TRSs

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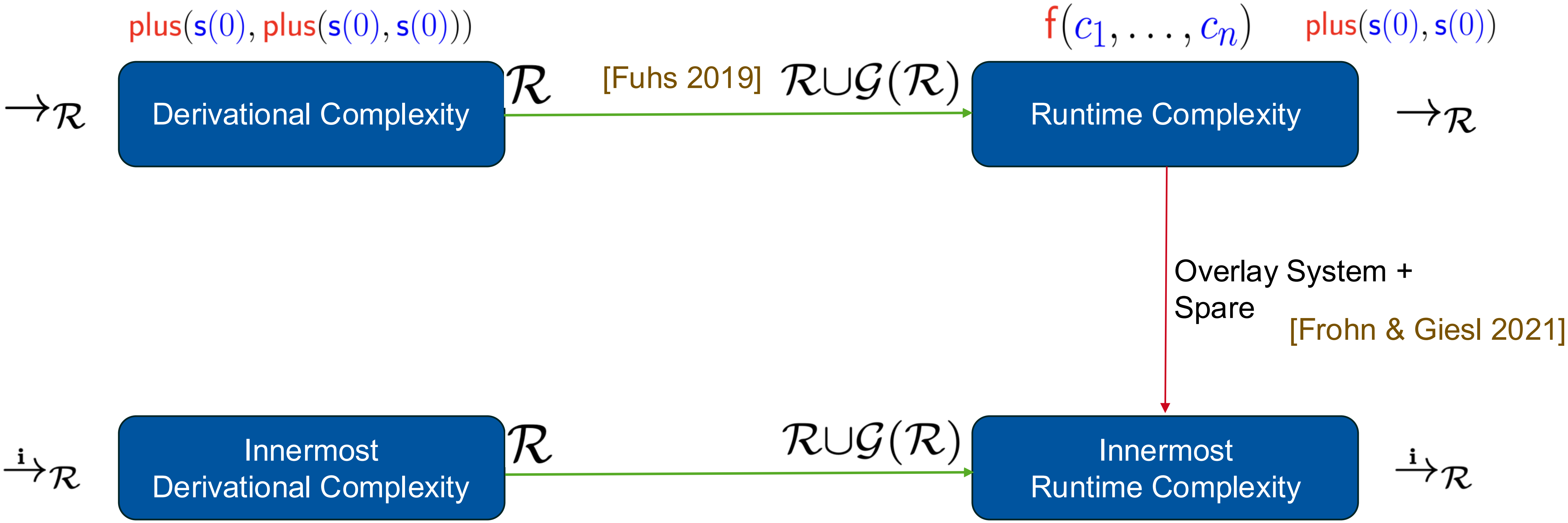

$\mathsf{plus}(\mathsf{s}(0), \mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0)))$

$\to_{\mathcal{R}}$

Derivational Complexity

$\mathcal{R}$

[Fuhs 2019] $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

$\mathsf{f}(c_1, \ldots, c_n)$ $\mathsf{plus}(\mathsf{s}(0), \mathsf{s}(0))$

Runtime Complexity

$\to_{\mathcal{R}}$

Overlay System + Spare

[Frohn & Giesl 2021]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Innermost Derivational Complexity

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Innermost Runtime Complexity

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Complexity of TRSs

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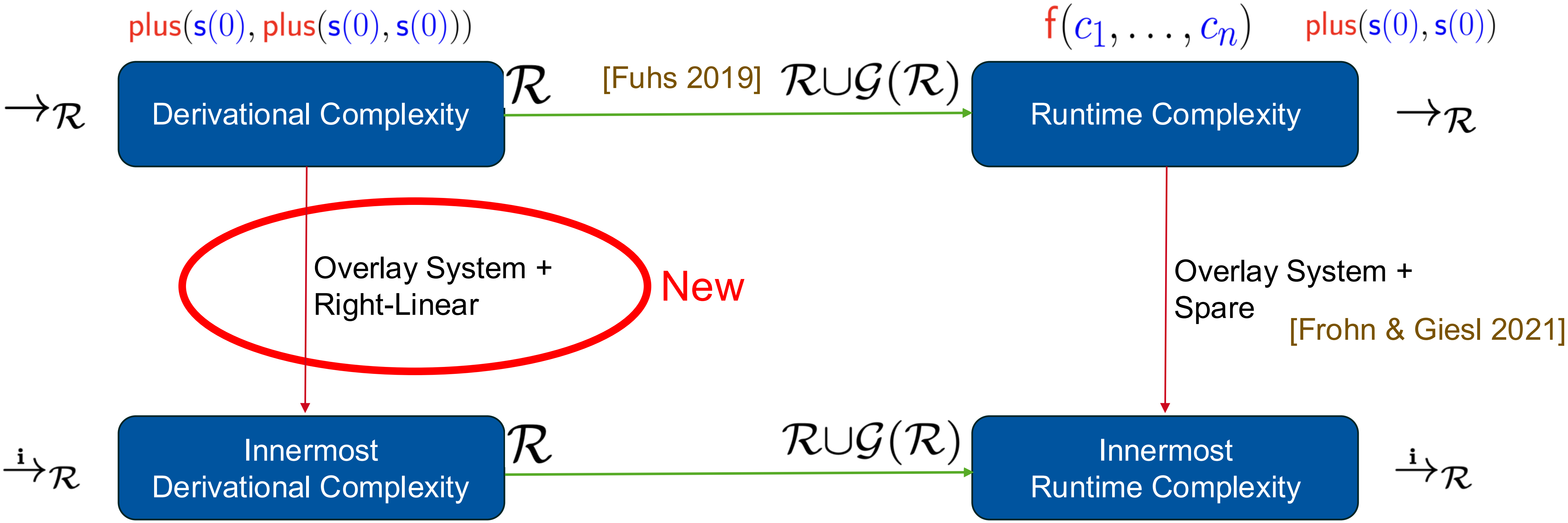

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$\to_{\mathcal{R}}$ Derivational Complexity $\mathcal{R}$ [Fuhs 2019] $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$ Runtime Complexity $\to_{\mathcal{R}}$

Overlay System +
Right-Linear

New

Overlay System +
Spare

[Frohn & Giesl 2021]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$ Innermost Derivational Complexity $\mathcal{R}$ $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$ Innermost Runtime Complexity $\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Termination of TRSs

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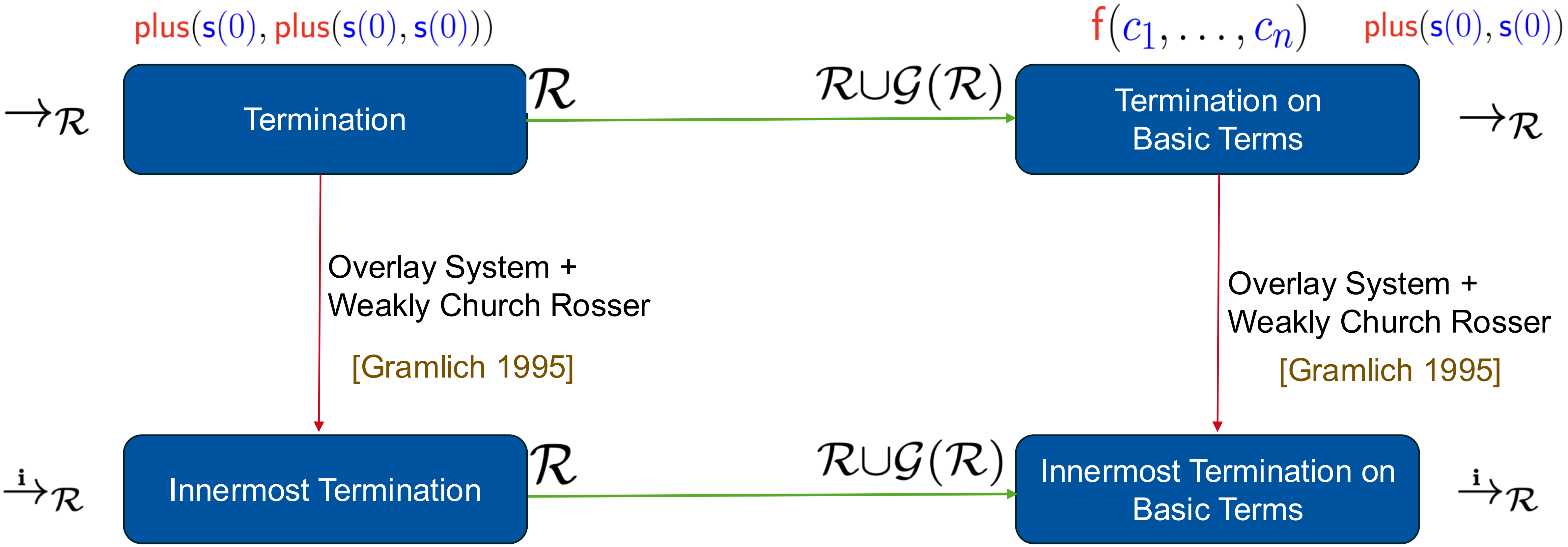

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$\to_{\mathcal{R}}$
Termination
$\mathcal{R}$
$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$
Termination on Basic Terms
$\to_{\mathcal{R}}$
Overlay System + Weakly Church Rosser
[Gramlich 1995]
Overlay System + Weakly Church Rosser
[Gramlich 1995]
$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$
Innermost Termination
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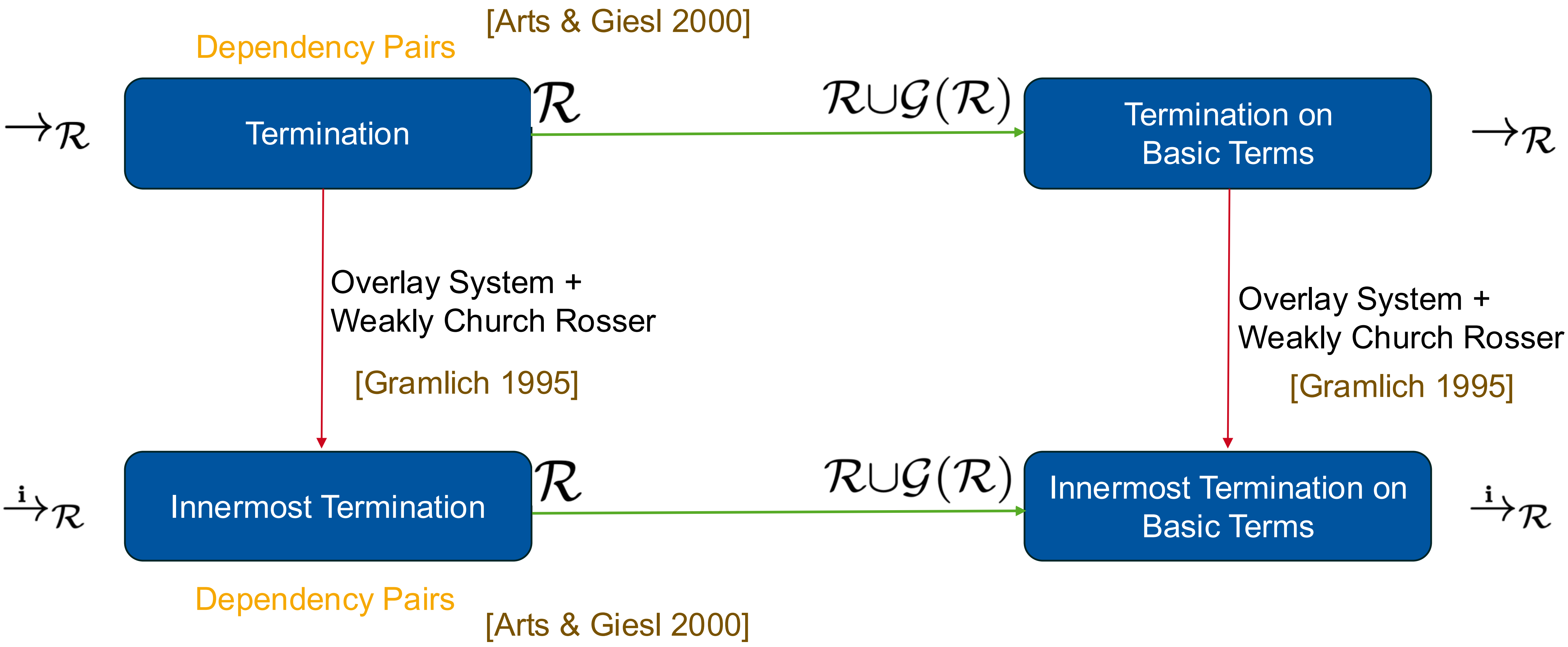

[Arts & Giesl 2000]

Dependency Pairs

$\to_{\mathcal{R}}$ Termination $\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$ Termination on Basic Terms $\to_{\mathcal{R}}$

Overlay System +
Weakly Church Rosser

[Gramlich 1995]

Overlay System +
Weakly Church Rosser

[Gramlich 1995]

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Dependency Pairs

[Arts & Giesl 2000]

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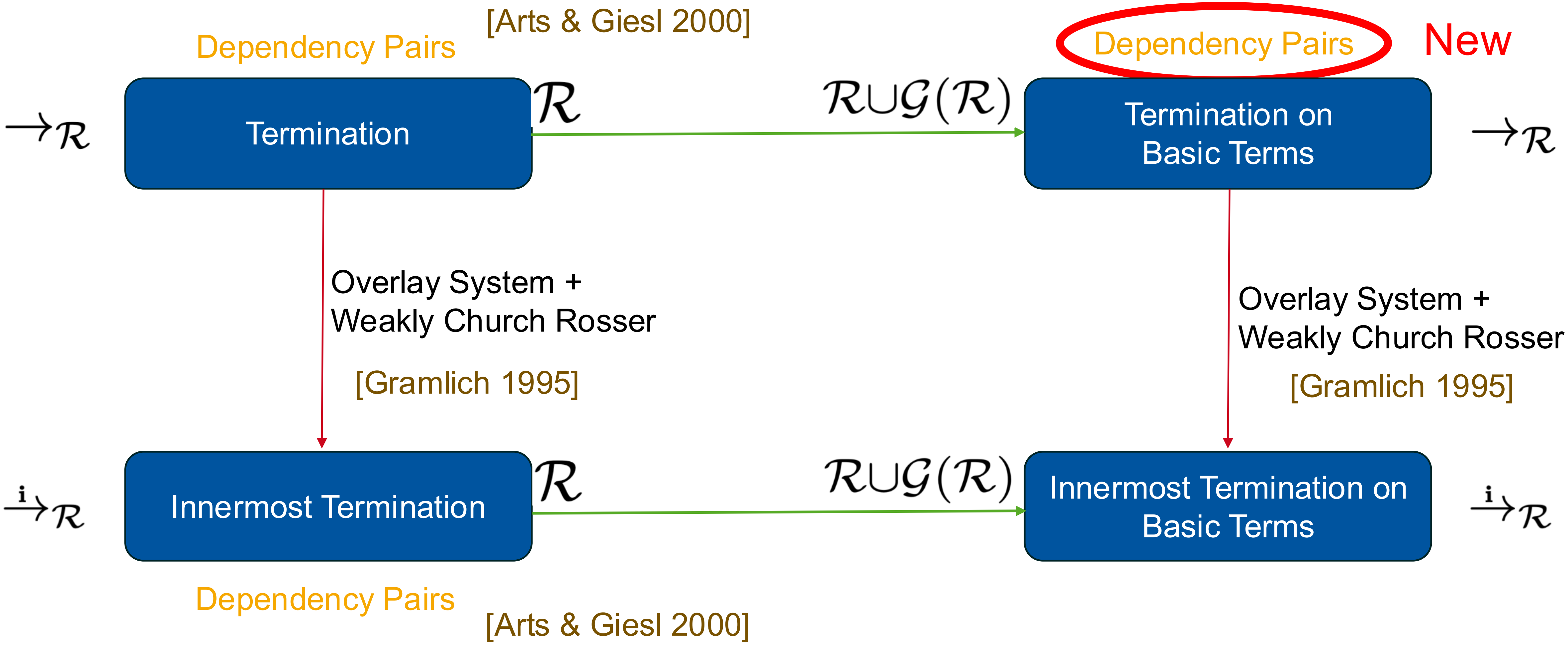

[Arts & Giesl 2000]

Dependency Pairs

Dependency Pairs

New

$\to_{\mathcal{R}}$

Termination

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Termination on Basic Terms

$\to_{\mathcal{R}}$

Overlay System + Weakly Church Rosser

[Gramlich 1995]

Overlay System + Weakly Church Rosser

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$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Innermost Termination

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Innermost Termination on Basic Terms

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Dependency Pairs

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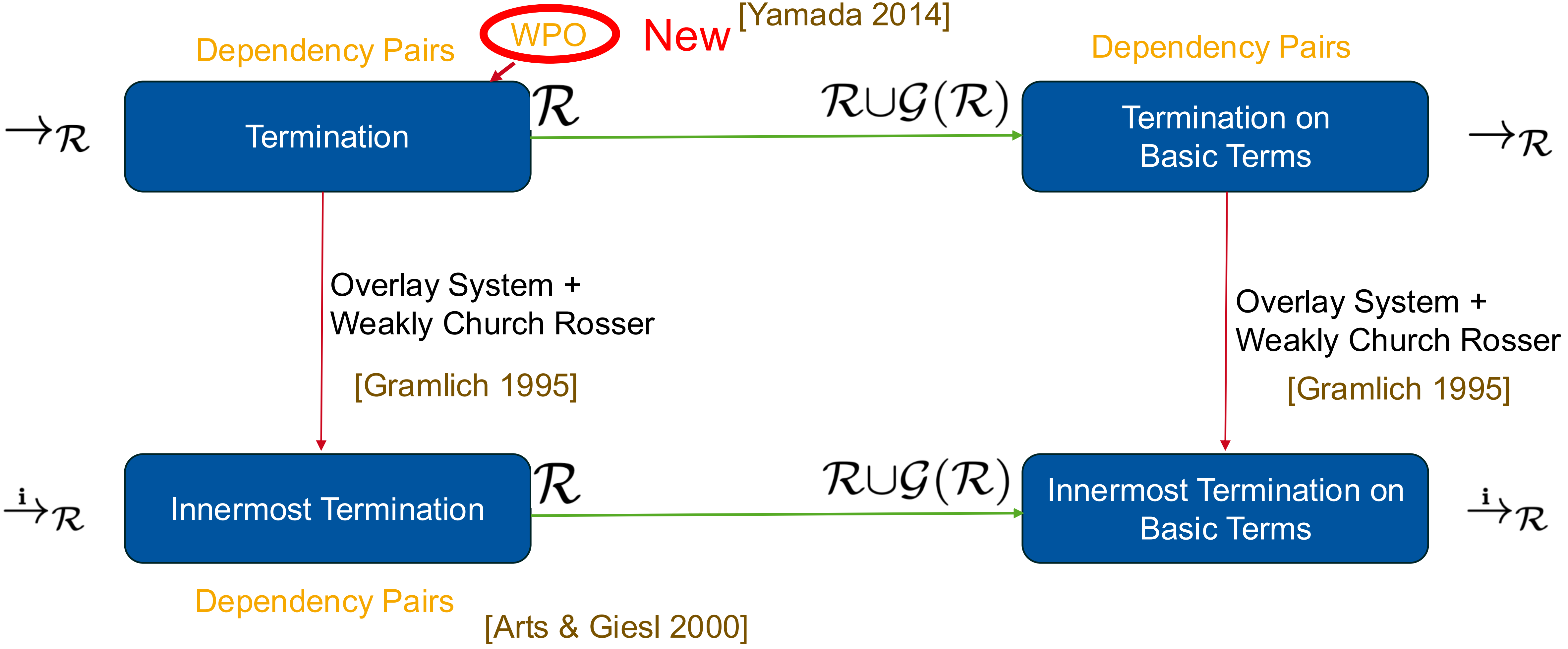

WPO

New

[Yamada 2014]

Dependency Pairs

$\to_{\mathcal{R}}$

Termination

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Dependency Pairs

Termination on Basic Terms

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Overlay System +
Weakly Church Rosser

[Gramlich 1995]

Overlay System +
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$\overset{\mathrm{i}}{\to}_{\mathcal{R}}$

Innermost Termination

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$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Innermost Termination on Basic Terms

$\overset{\mathrm{i}}{\to}_{\mathcal{R}}$

Dependency Pairs

[Arts & Giesl 2000]

Almost-Sure Termination of Probabilistic TRSs

$$\mathsf{g} \to \{1/2 : 0,\ 1/2 : \mathsf{g}\}$$

$\to_{\mathcal{R}}$ AST

AST on Basic Terms $\to_{\mathcal{R}}$

$\xrightarrow{\mathbf{i}}_{\mathcal{R}}$ Innermost AST

Innermost AST on Basic Terms $\xrightarrow{\mathbf{i}}_{\mathcal{R}}$

Almost-Sure Termination of Probabilistic TRSs

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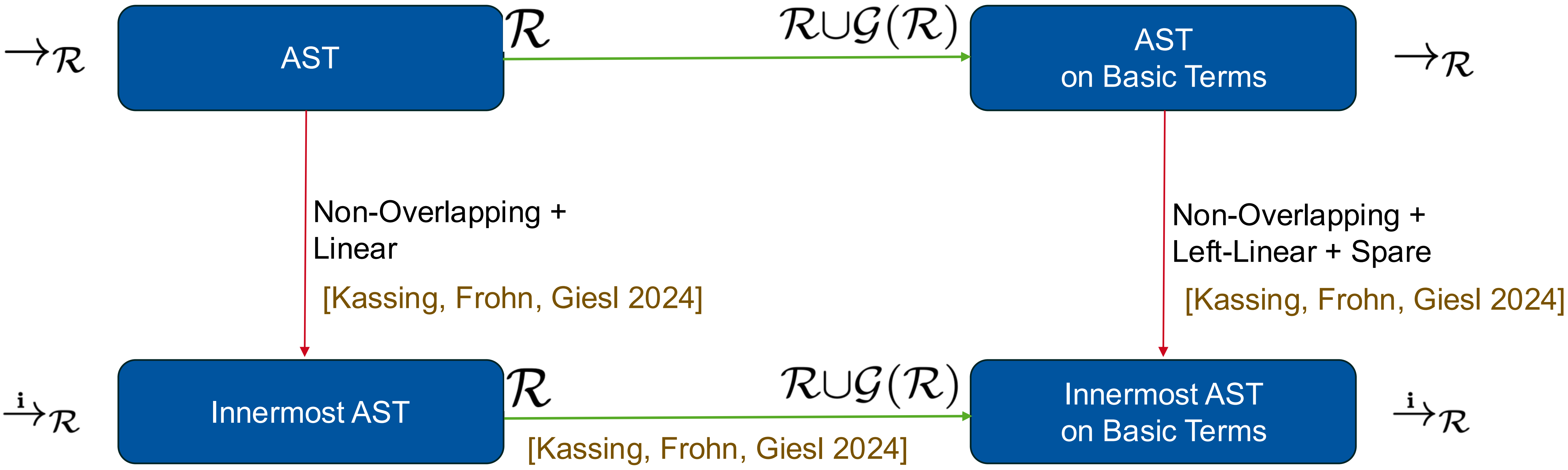

$\to_{\mathcal{R}}$

AST

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

AST
on Basic Terms

$\to_{\mathcal{R}}$

Non-Overlapping +
Linear

[Kassing, Frohn, Giesl 2024]

Non-Overlapping +
Left-Linear + Spare

[Kassing, Frohn, Giesl 2024]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Innermost AST

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Innermost AST
on Basic Terms

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[Kassing, Frohn, Giesl 2024]

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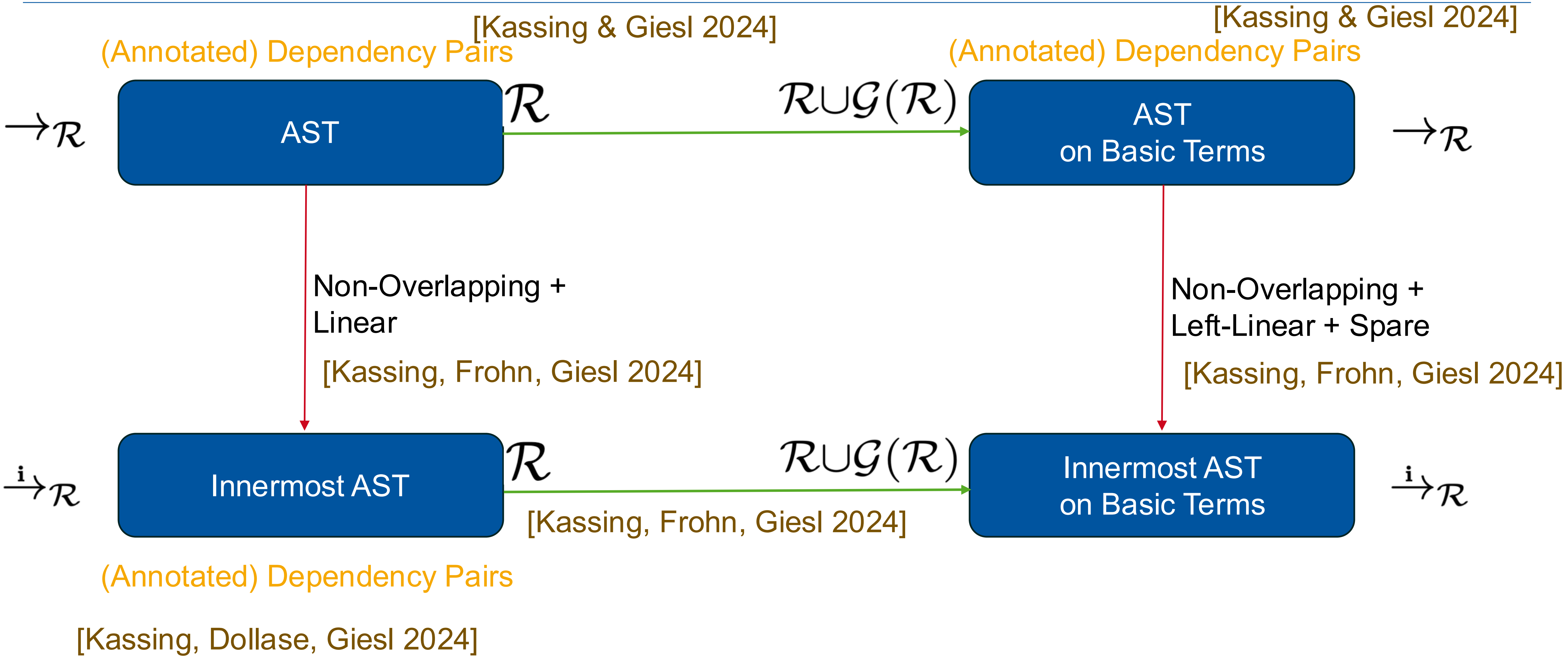

[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

$\to_{\mathcal{R}}$ AST

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

AST on Basic Terms $\to_{\mathcal{R}}$

Non-Overlapping + Linear

[Kassing, Frohn, Giesl 2024]

Non-Overlapping + Left-Linear + Spare

[Kassing, Frohn, Giesl 2024]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$ Innermost AST

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[Kassing, Frohn, Giesl 2024]

Innermost AST on Basic Terms $\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

(Annotated) Dependency Pairs

[Kassing, Dollase, Giesl 2024]

Almost-Sure Termination of Probabilistic TRSs

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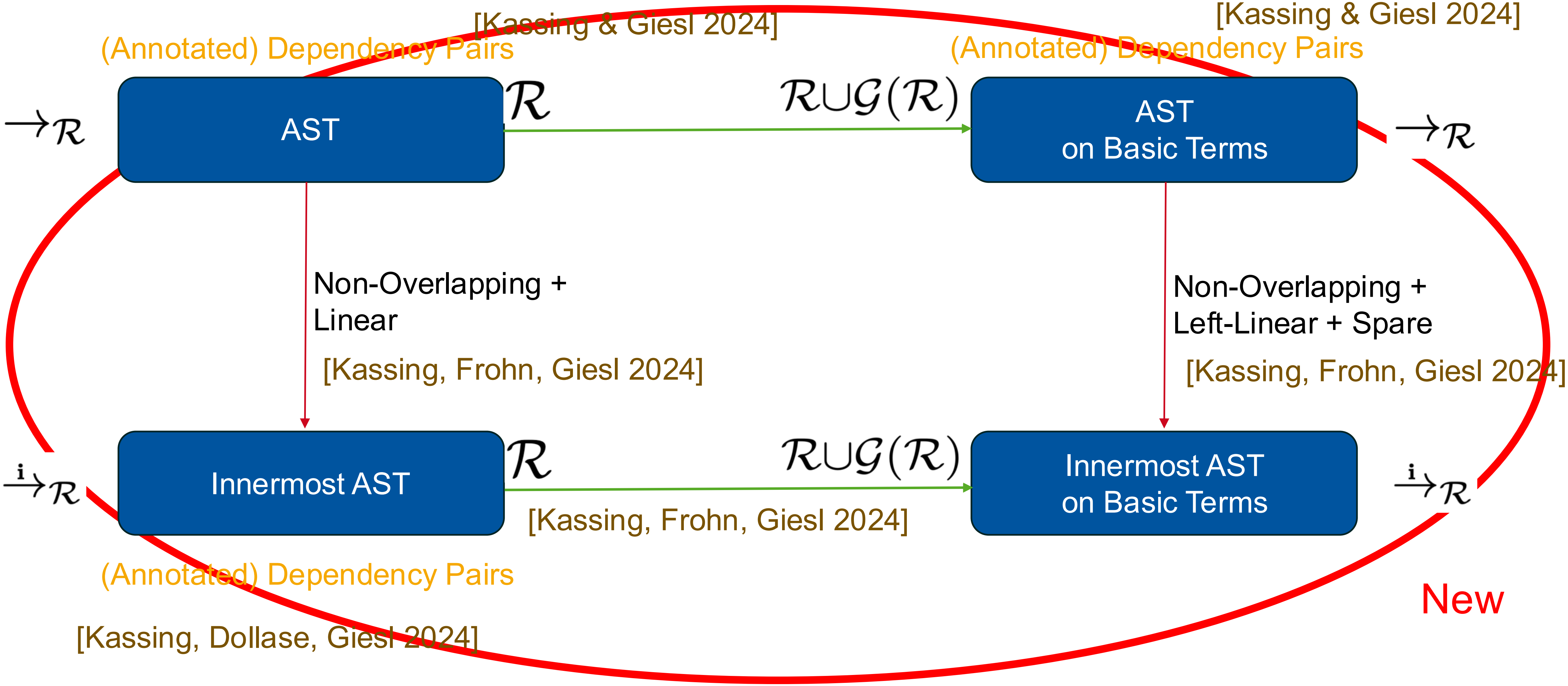

[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

$\to_{\mathcal{R}}$

AST

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

AST
on Basic Terms

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[Kassing, Frohn, Giesl 2024]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Innermost AST

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing, Frohn, Giesl 2024]

Innermost AST
on Basic Terms

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

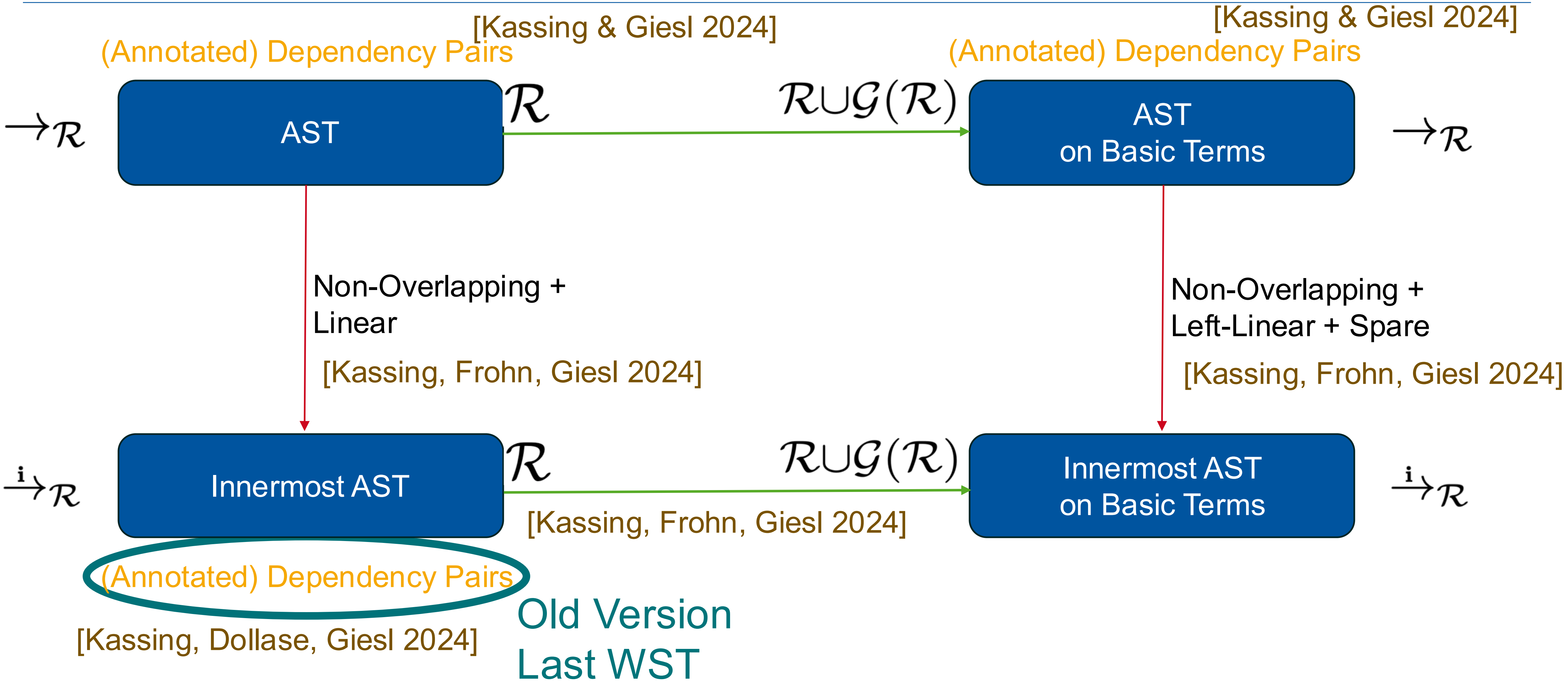
(Annotated) Dependency Pairs

[Kassing, Dollase, Giesl 2024]

New

Almost-Sure Termination of Probabilistic TRSs

$\mathsf{g} \to \{1/2 : 0,\ 1/2 : \mathsf{g}\}$



[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

$\to_{\mathcal{R}}$ AST

$\mathcal{R}$ $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing & Giesl 2024]

(Annotated) Dependency Pairs

AST on Basic Terms $\to_{\mathcal{R}}$

Non-Overlapping + Linear

[Kassing, Frohn, Giesl 2024]

Non-Overlapping + Left-Linear + Spare

[Kassing, Frohn, Giesl 2024]

$\xrightarrow{\mathbf{i}}_{\mathcal{R}}$ Innermost AST

$\mathcal{R}$ $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing, Frohn, Giesl 2024]

Innermost AST on Basic Terms $\xrightarrow{\mathbf{i}}_{\mathcal{R}}$

(Annotated) Dependency Pairs

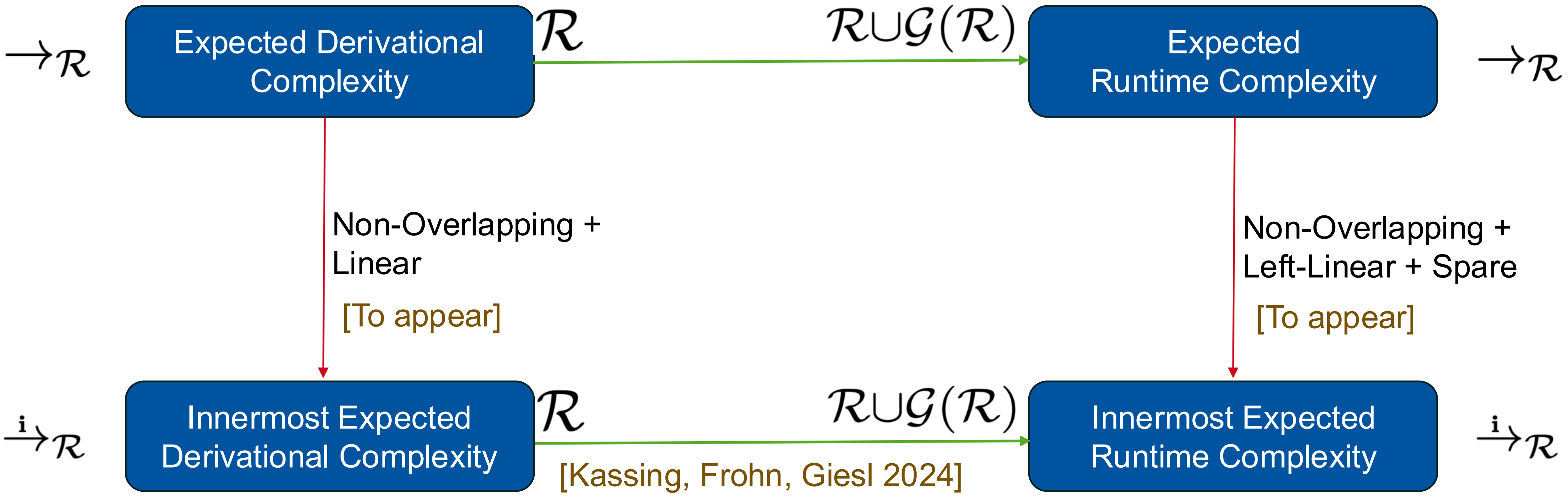
[Kassing, Dollase, Giesl 2024]

Old Version

Last WST

Expected Complexity of Probabilistic TRSs

$\mathsf{g} \to \{ 1/2 : 0,\ 1/2 : \mathsf{g} \}$



$\to_{\mathcal{R}}$

Expected Derivational Complexity

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Expected Runtime Complexity

$\to_{\mathcal{R}}$

Non-Overlapping + Linear

[To appear]

Non-Overlapping + Left-Linear + Spare

[To appear]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

Innermost Expected Derivational Complexity

$\mathcal{R}$

$\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing, Frohn, Giesl 2024]

Innermost Expected Runtime Complexity

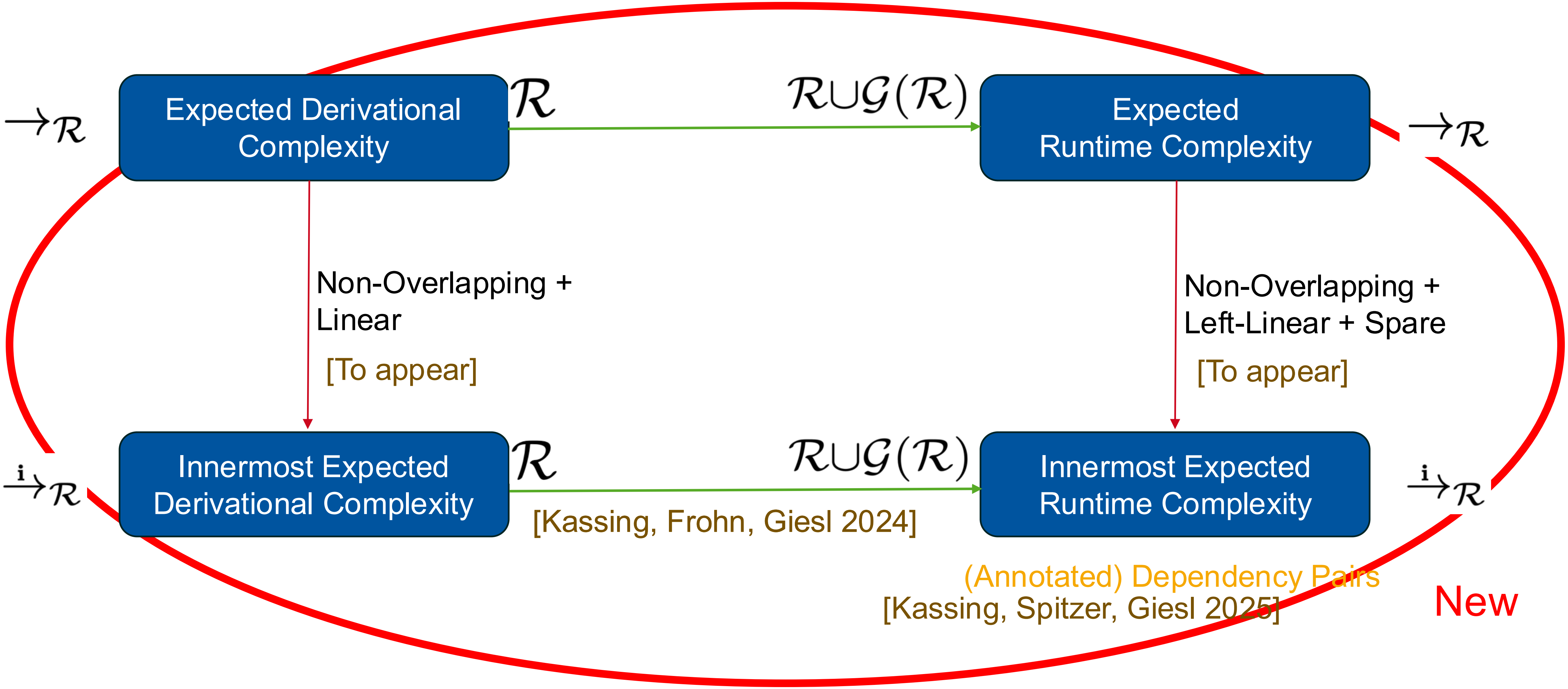
$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

(Annotated) Dependency Pairs

[Kassing, Spitzer, Giesl 2025]

Expected Complexity of Probabilistic TRSs

$\mathsf{g} \to \{{}^{1}/_{2} : 0,\ {}^{1}/_{2} : \mathsf{g}\}$



$\to_{\mathcal{R}}$ Expected Derivational Complexity

$\mathcal{R}$ → $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

Expected Runtime Complexity $\to_{\mathcal{R}}$

Non-Overlapping + Linear

[To appear]

Non-Overlapping + Left-Linear + Spare

[To appear]

$\xrightarrow{\mathrm{i}}_{\mathcal{R}}$ Innermost Expected Derivational Complexity

$\mathcal{R}$ → $\mathcal{R} \cup \mathcal{G}(\mathcal{R})$

[Kassing, Frohn, Giesl 2024]

Innermost Expected Runtime Complexity $\xrightarrow{\mathrm{i}}_{\mathcal{R}}$

(Annotated) Dependency Pairs

[Kassing, Spitzer, Giesl 2025]

New

Everything New:

  - **TRS**:
    - Implemented WPO
    - Dependency Pairs for Basic Startterms
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Everything New:

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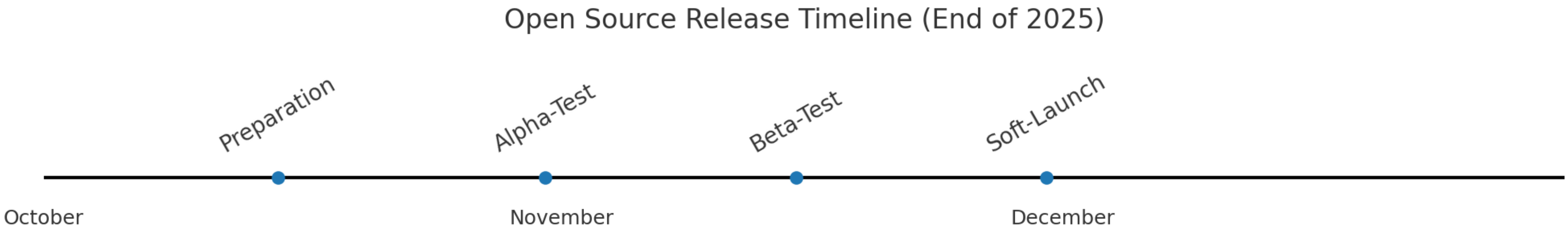
Open Source Release



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Future Work / Current Research / Miscellaneous

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If you are interested in one of these topics, feel free to talk to me!

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Storm

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