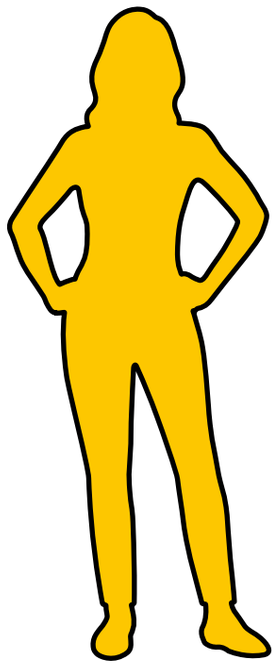
Dynamic Set Reasoning

SPECIFYING AND OPTIMIZING MONITOR ENCODINGS

Chris Johannsen

IOWA STATE UNIVERSITY

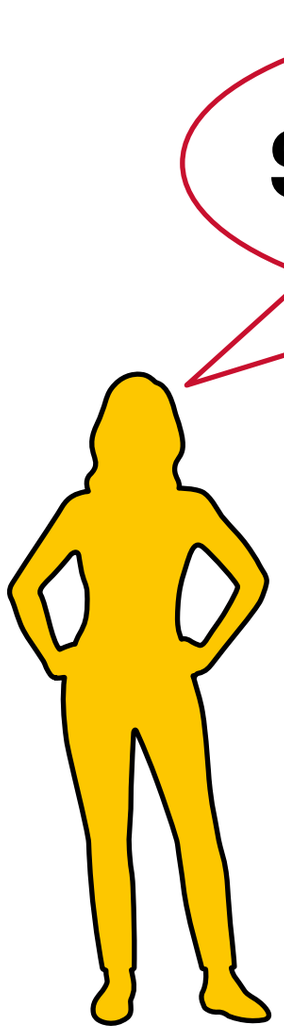
Sam the Satellite Engineer



Sam

[2]

Sam the Satellite Engineer



[2]

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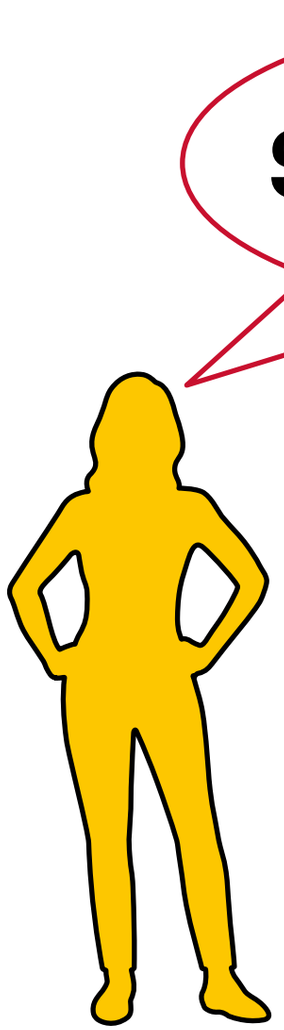
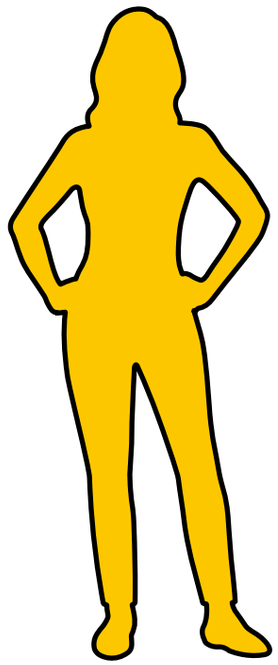


[2]

How to detect and diagnose “stuff”?

Sam the Satellite Engineer



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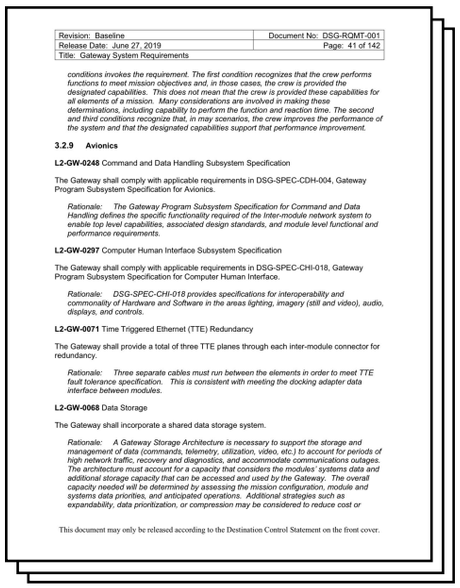

Revision: Baseline	Document No: DSG-RQMT-001
Release Date: June 27, 2019	Page: 41 of 142
Title: Gateway System Requirements	

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3.2.9 Avionics

L2-GW-0248 Command and Data Handling Subsystem Specification

The Gateway shall comply with applicable requirements in DSG-SPEC-CDH-004, Gateway Program Subsystem Specification for Avionics.

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[4]

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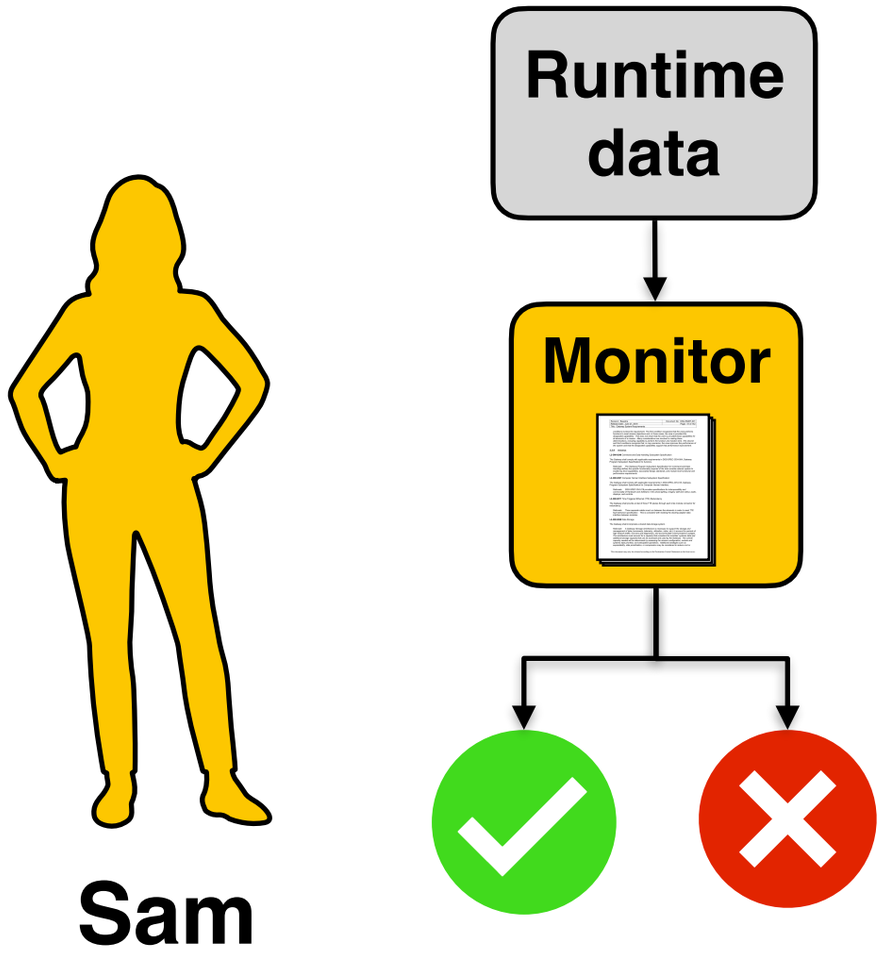

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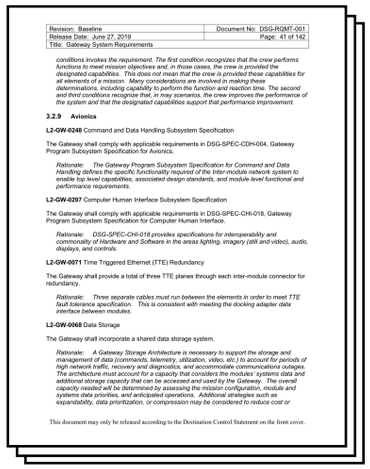

Revision: Baseline | Document No: DSG-RQMT-001
Release Date: June 27, 2019 | Page: 41 of 142
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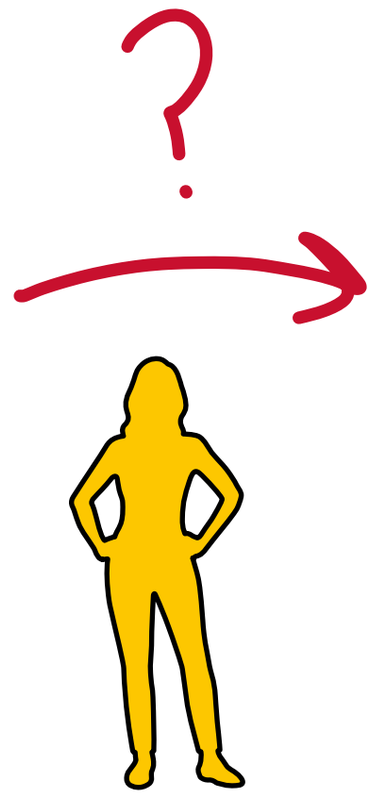

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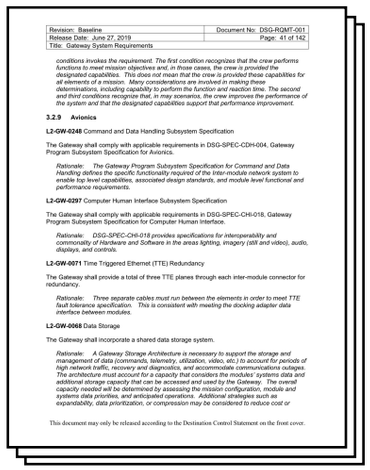

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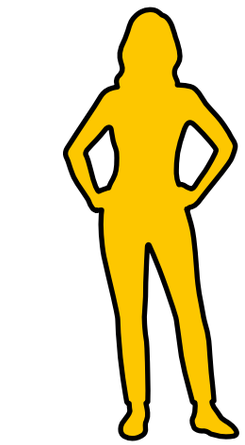
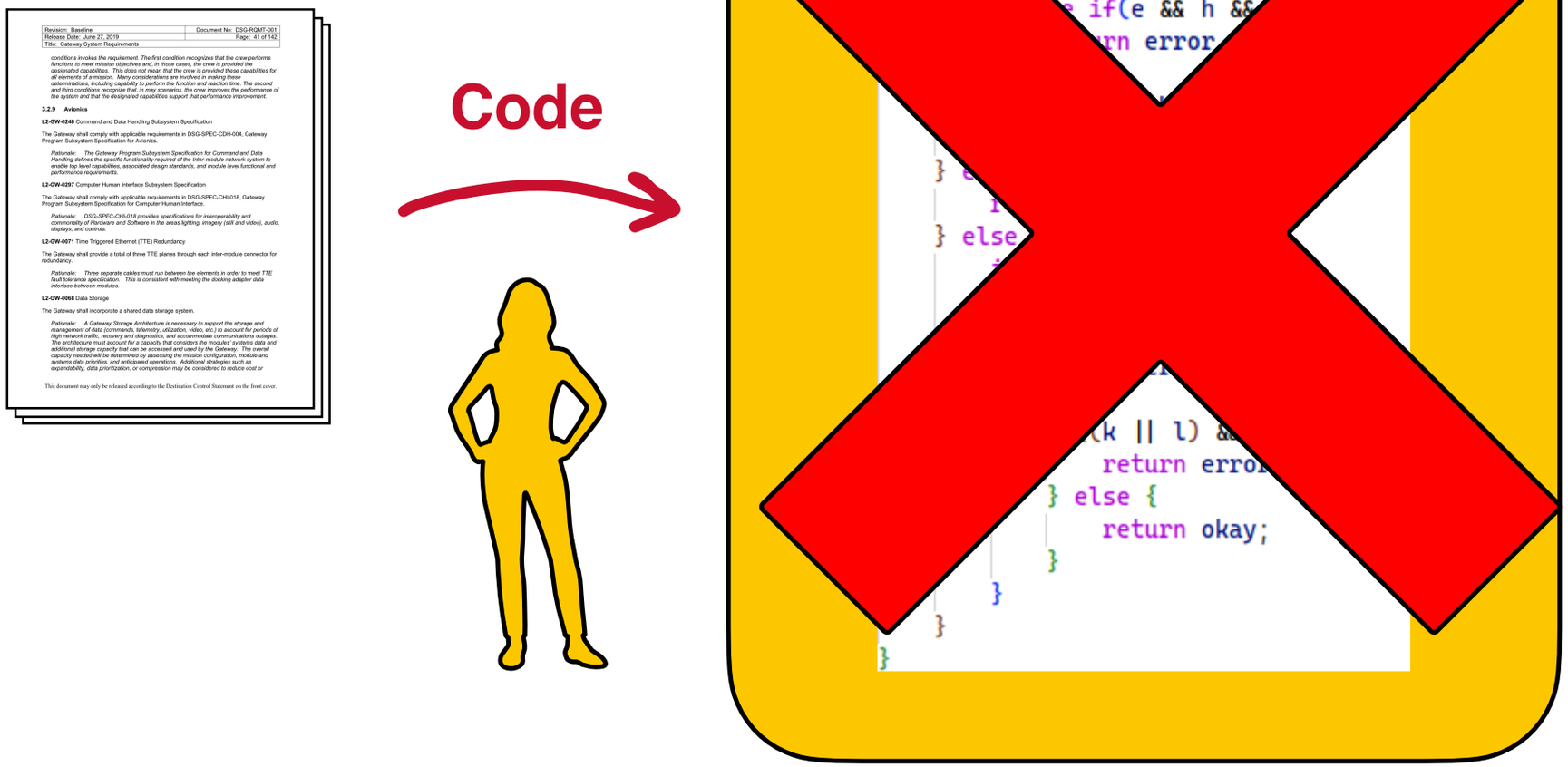


Monitor

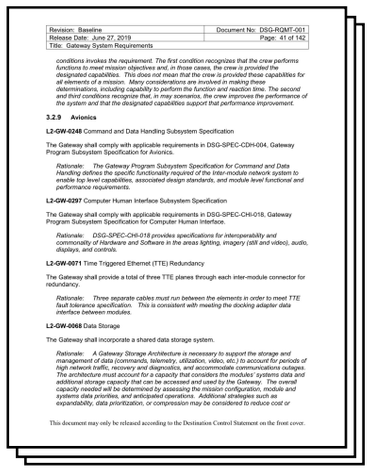
```
if(a && b) {
    if(!c || d) {
        return error_0;
    } else if(c || d) {
        if (e && f && g) {
            return error_1;
        } else if(e && h && g) {
            return error_2;
        } else {
            return okay;
        }
    } else if(d) {
        return error_1;
    } else {
        if(i && !j) {
            return error_4;
        } else if(!i && j) {
            return error_5;
        } else {
            if((k || l) && (k == m)) {
                return error_6;
            } else {
                return okay;
            }
        }
    }
}
```

How does Sam implement a monitor?



How does Sam implement a monitor?

- Re-certification
- Opaque



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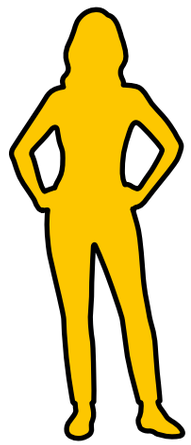
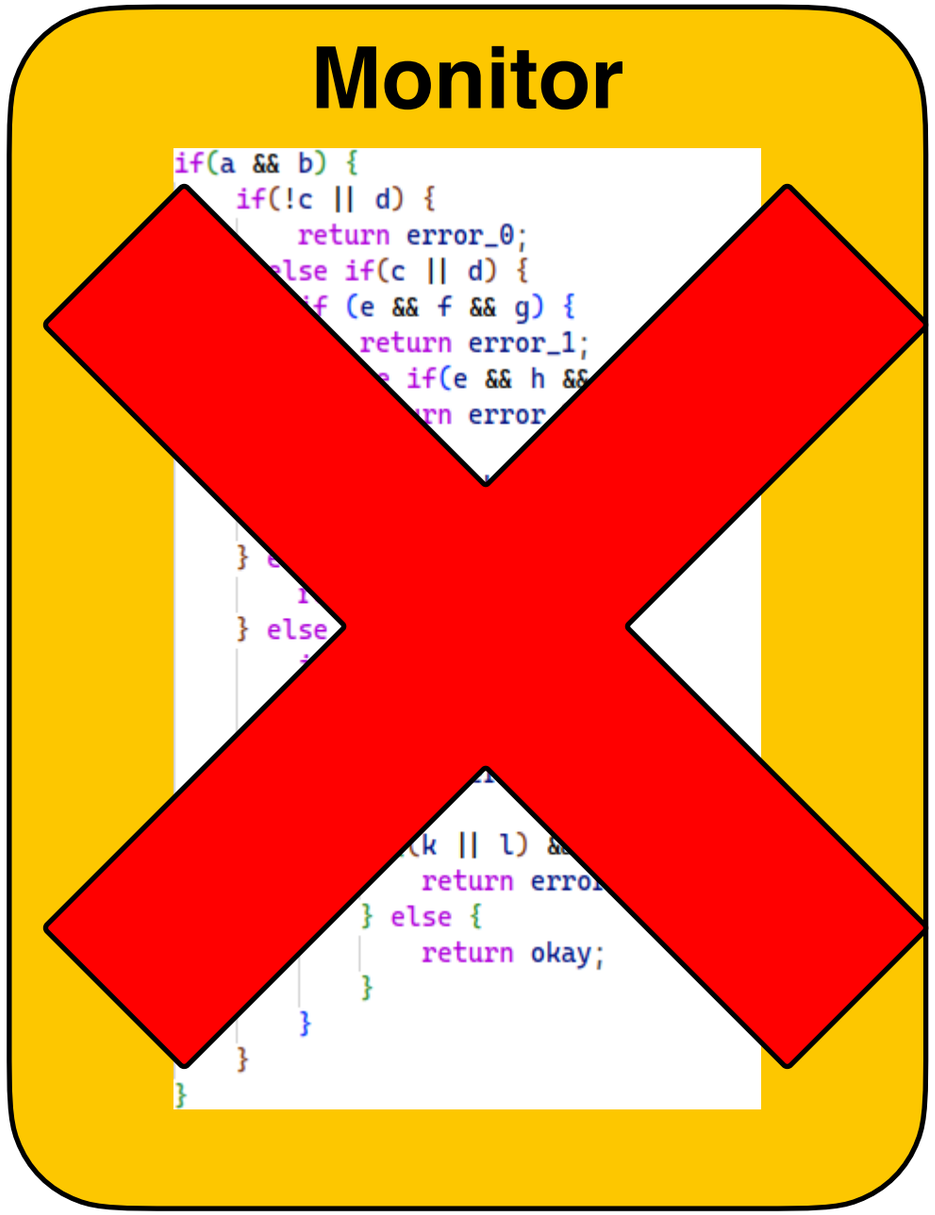
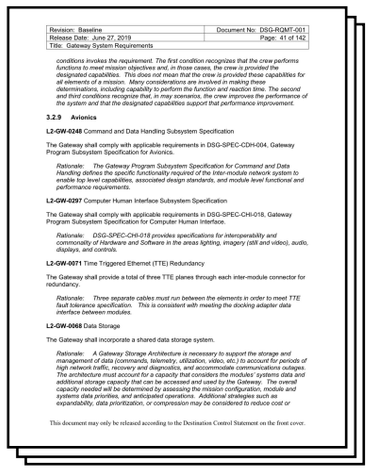




Runtime Verification (RV) Approach


Revision: Baseline | Document No: DSG-RQMT-001
Release Date: June 27, 2019 | Page: 41 of 142
Title: Gateway System Requirements

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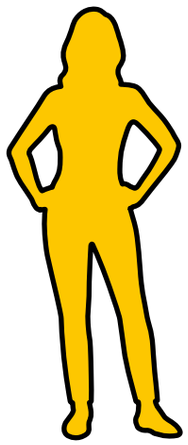
Formalize



- Temporal Logic
- Automata
- LOLA [5]

Generate

Monitor

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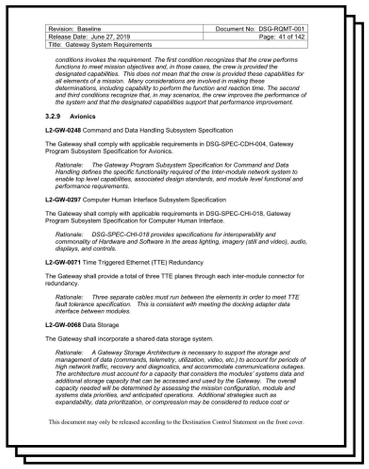
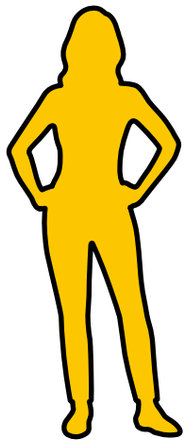


What to use?

Formalize



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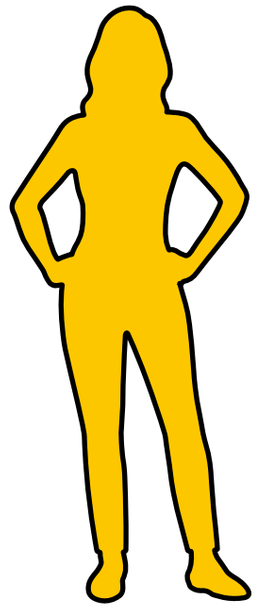
Generate

Monitor

Which RV tool to use?

Sam's constraints (**embedded, real-time, safety-critical**):

- **Realizable**
- **Responsive**
- **Unobtrusive**



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  - Use **bounded, little** resources
  - Adapt to new specifications **without re-compilation**
  - **Expressive, intuitive** specification language
- **Responsive**
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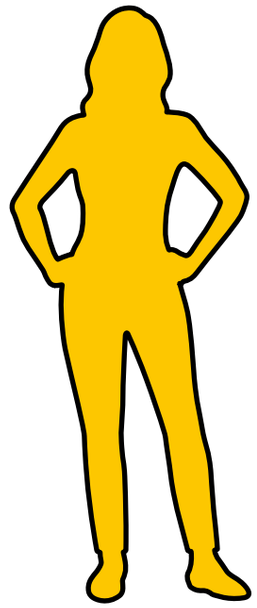

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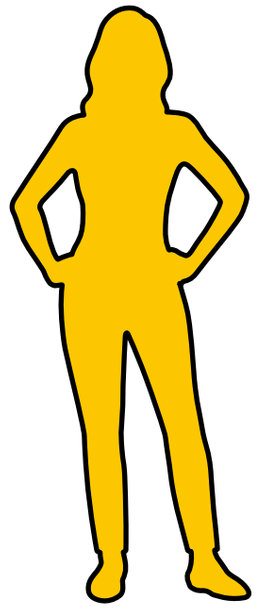
  - Runs continuously
  - Provides results **as soon as available**
- **Unobtrusive**



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- **Responsive**
  - Runs continuously
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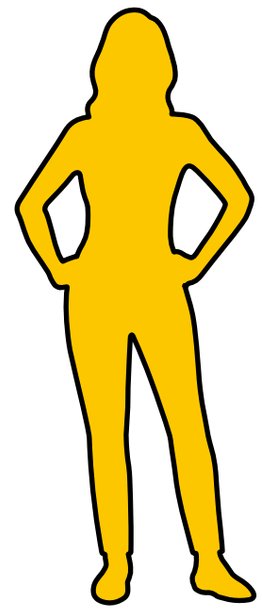
- **Unobtrusive**
  - Does not impact **certifiability/functionality/behavior**
  - Black box



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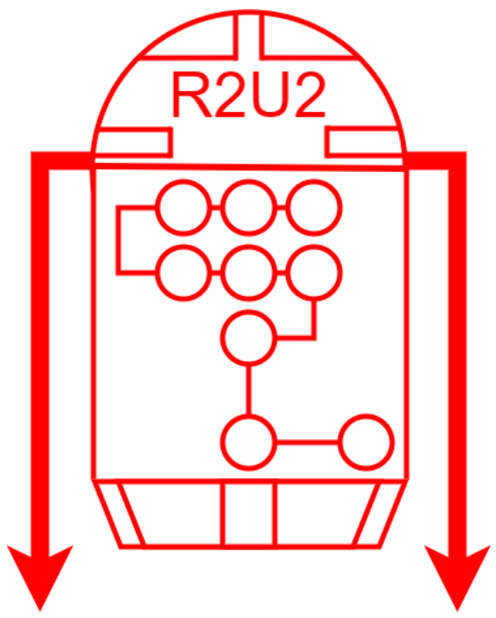
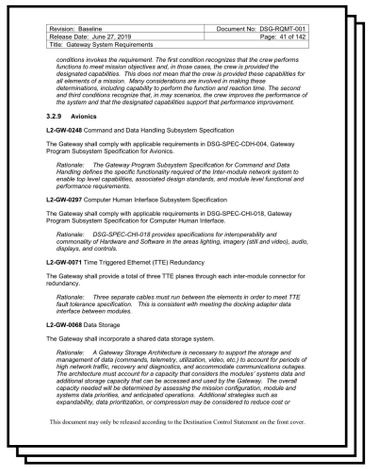
- **Unit**



R2U2 Approach



Revision: Baseline | Document No: DSG-RQMT-001
Release Date: June 27, 2019 | Page: 41 of 142
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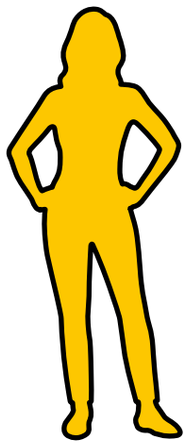

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Monitor

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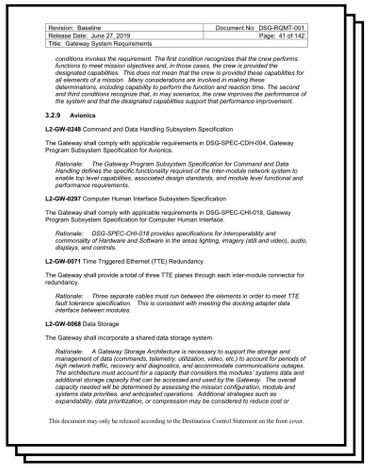

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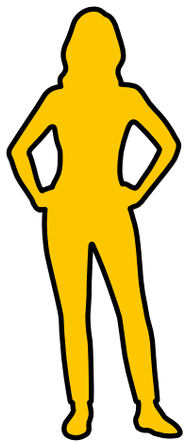
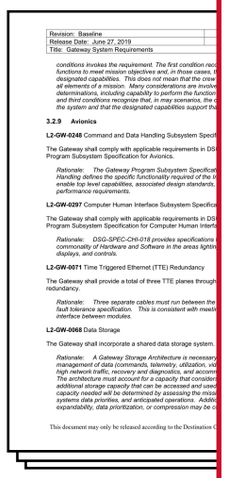


Mission-time LTL

Generate

Monitor

R2U2 Approach


Revision: Baseline
Release Date: June 27, 2019
Title: Gateway System Requirements

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3.2.9 Avionics

L2-GW-0248 Command and Data Handling Subsystem Specifi

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The Gateway shall provide a total of three TTE planes through
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*Rationale: Three separate cables must run between the
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The Gateway shall incorporate a shared data storage system.

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Mission-time LTL

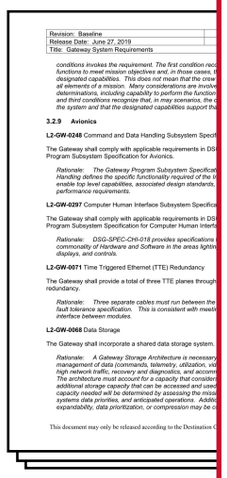
(MLTL) [16]

“If ‘task’ is in the scheduler, ‘task’ shall execute within 3 seconds ”

itor

$$(sched_{task}) \rightarrow (\Diamond_{[0,3]} exec_{task})$$

R2U2 Approach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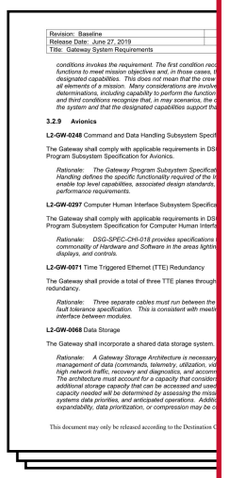
Propositions

R2U2 Approach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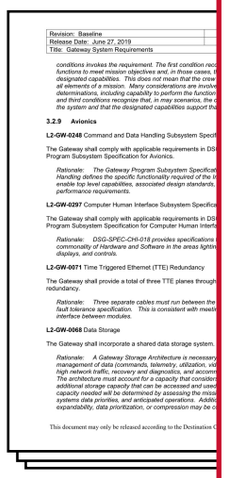
Logical connectives ($\rightarrow$, $\neg$, $\wedge$, $\vee$)

itor

R2U2 Approach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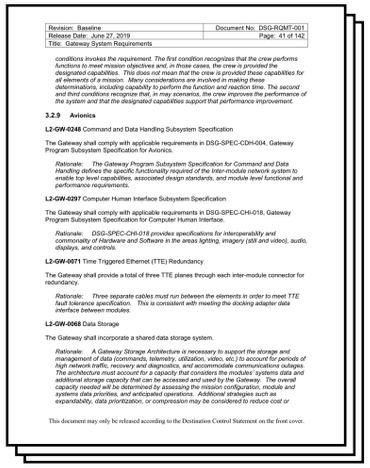
Future-time, bounded ops

R2U2 Approach



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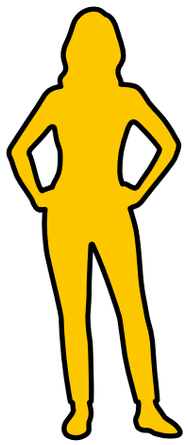
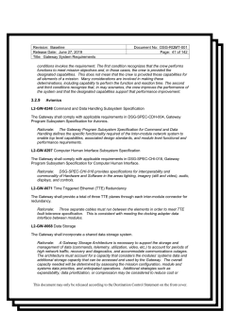


Mission-time LTL

Generate

Monitor

R2U2 Approach



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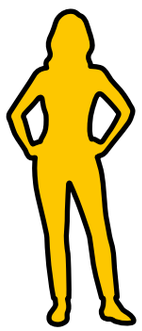

Mission-time LTL

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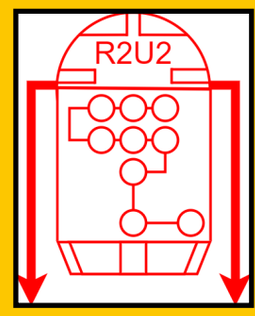
.bin

Monitor



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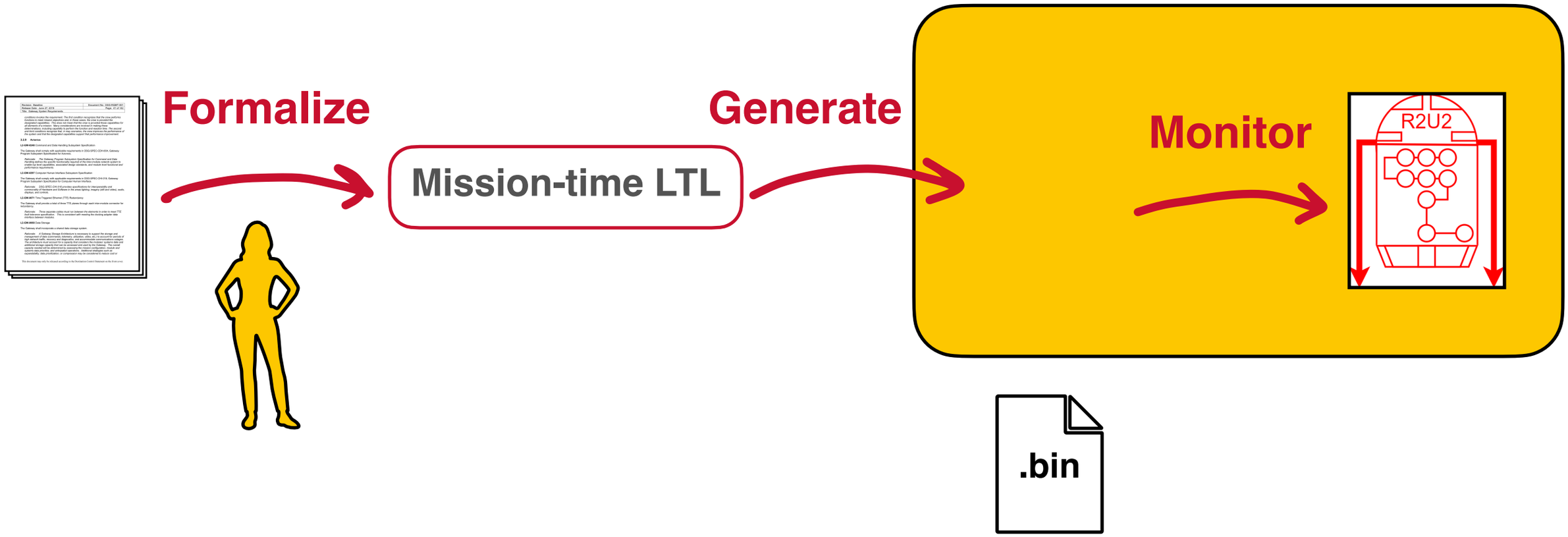

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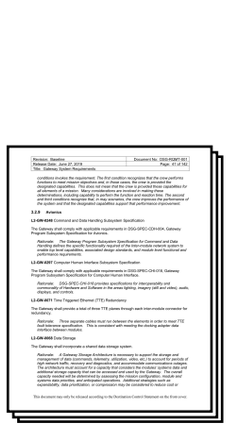

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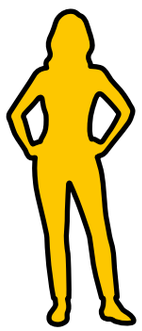

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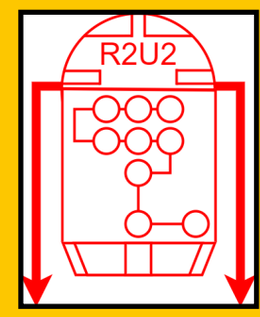

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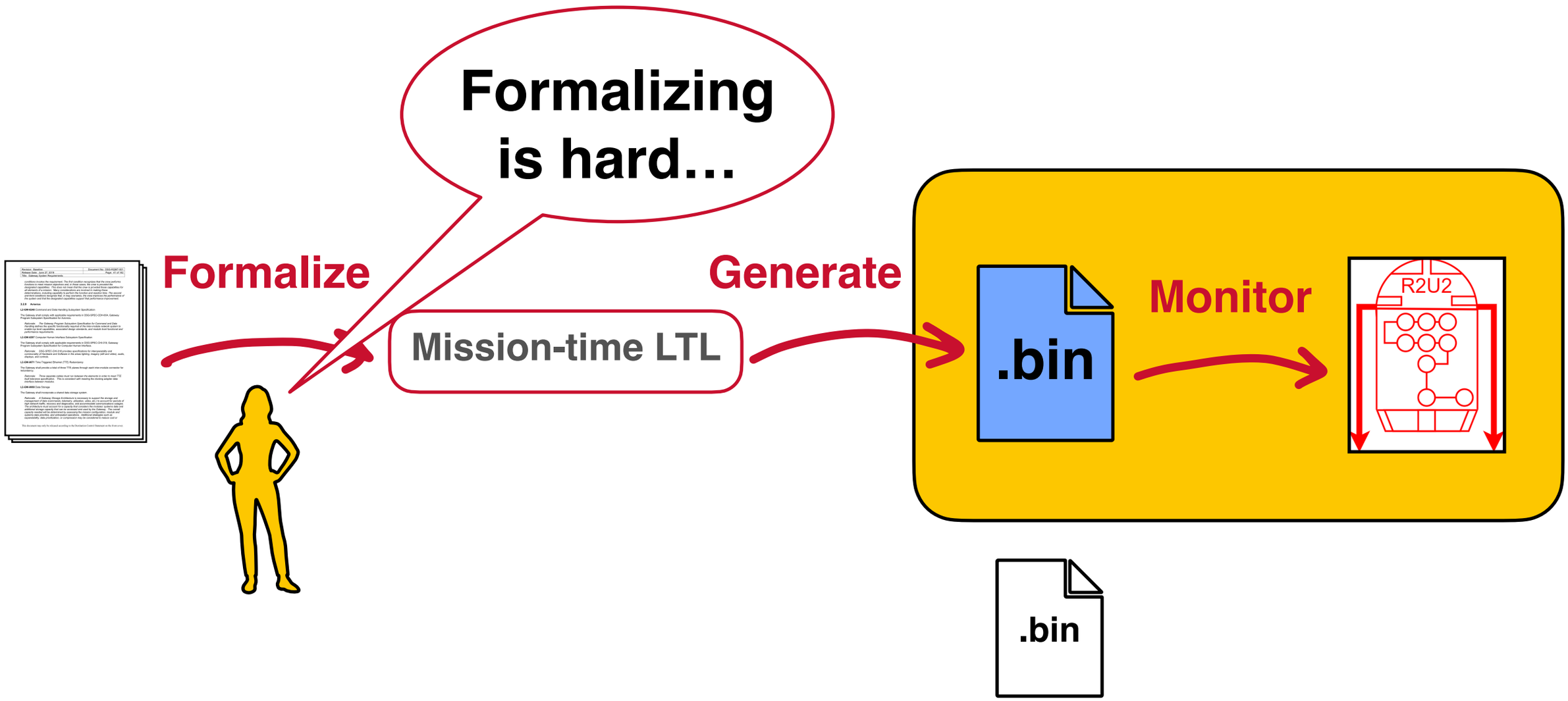
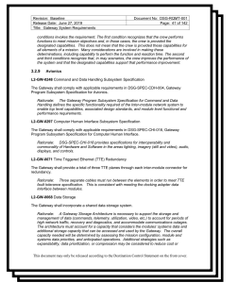


R2U2 + C2PO Approach

Configuration Compiler for Property Organization (C2PO) [17]



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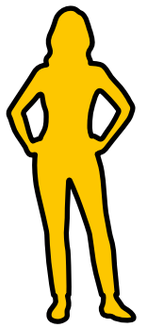

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FTSPEC
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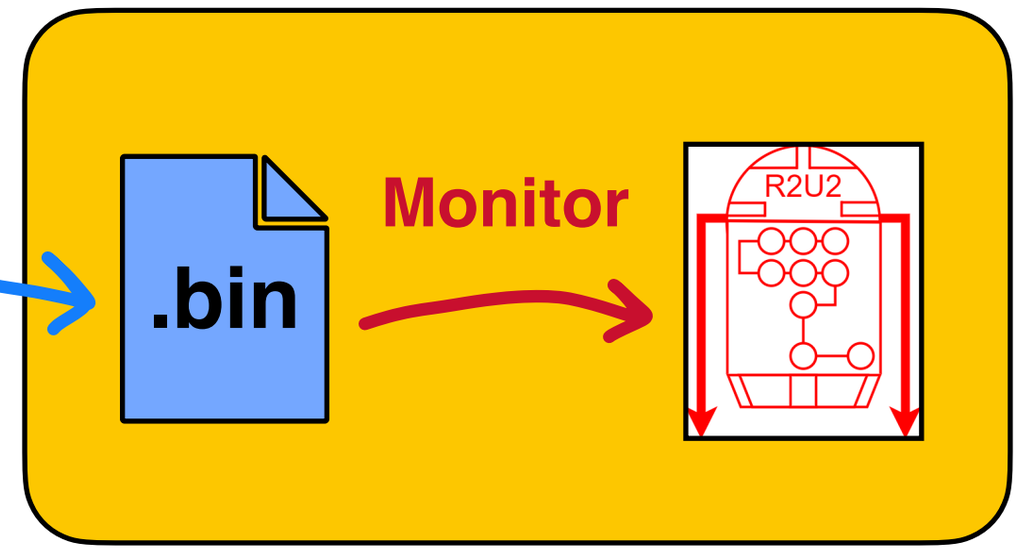
```

High-level language

Generate



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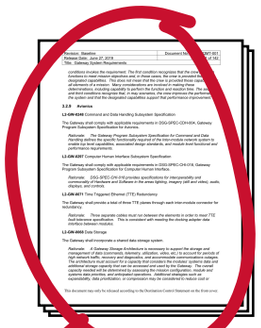

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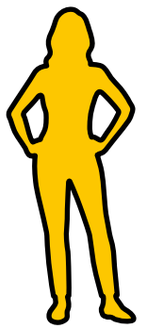

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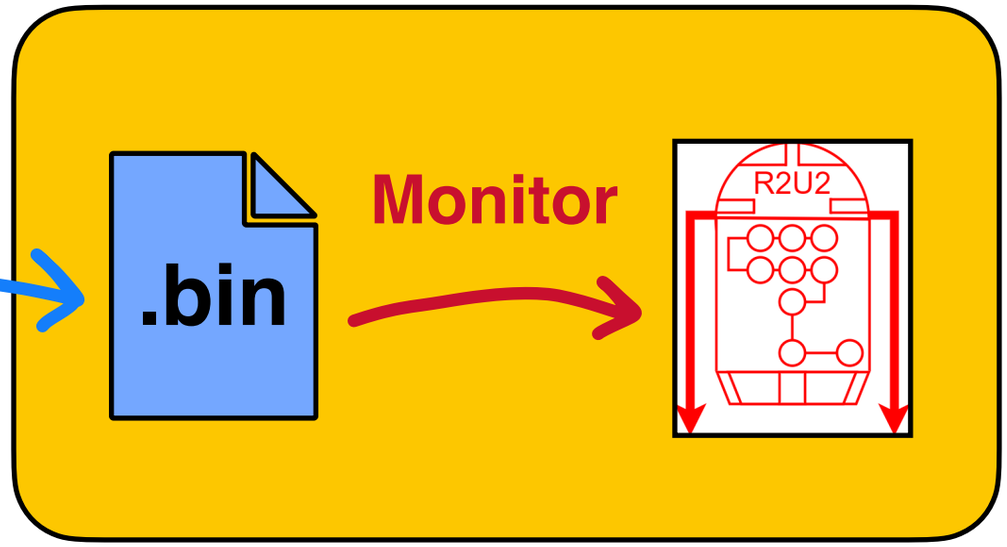

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Sam's Specification Revisited

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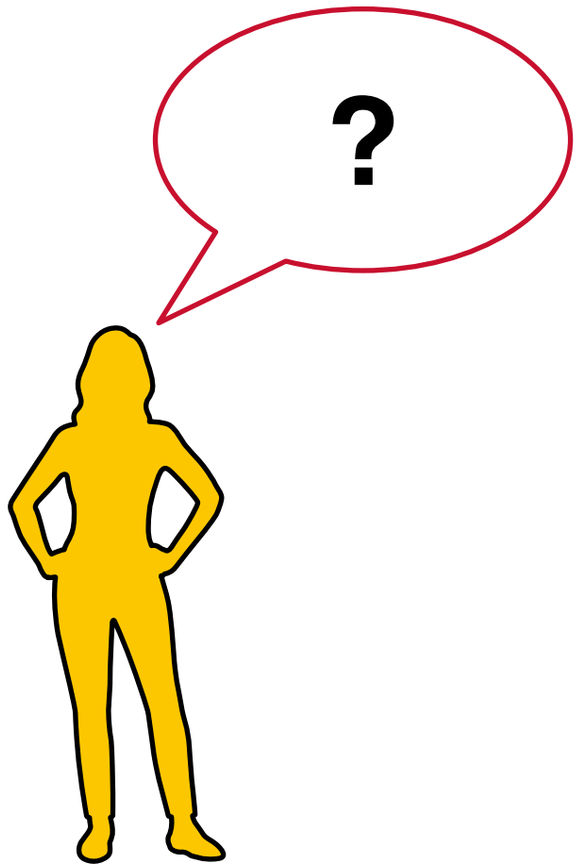

Sam's Specification Revisited

Every task in the scheduler

"~~If 'task' is in the scheduler, 'task~~' shall execute within 3 seconds "

Sam's Specification Revisited

Every task in the scheduler

"~~If 'task' is in the scheduler, 'task~~" shall execute within 3 seconds "

Formalize

$$\square \; \forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Sam's Specification Revisited

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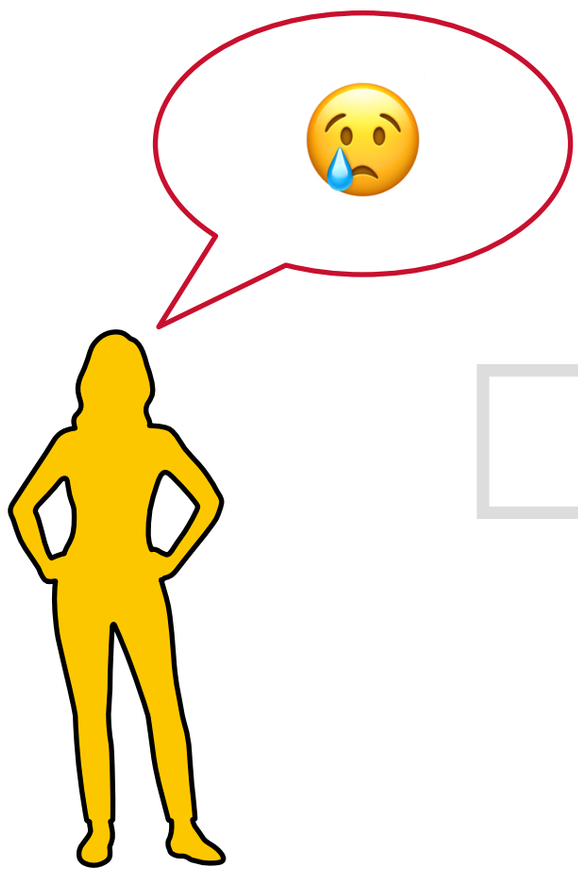

Formalize

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Can't use R2U2

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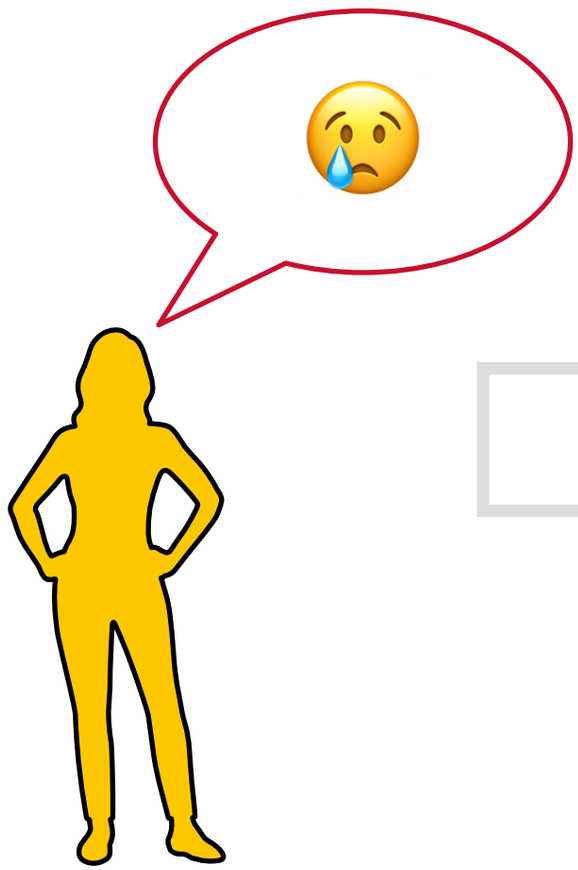

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Can't use R2U2 …or can she?

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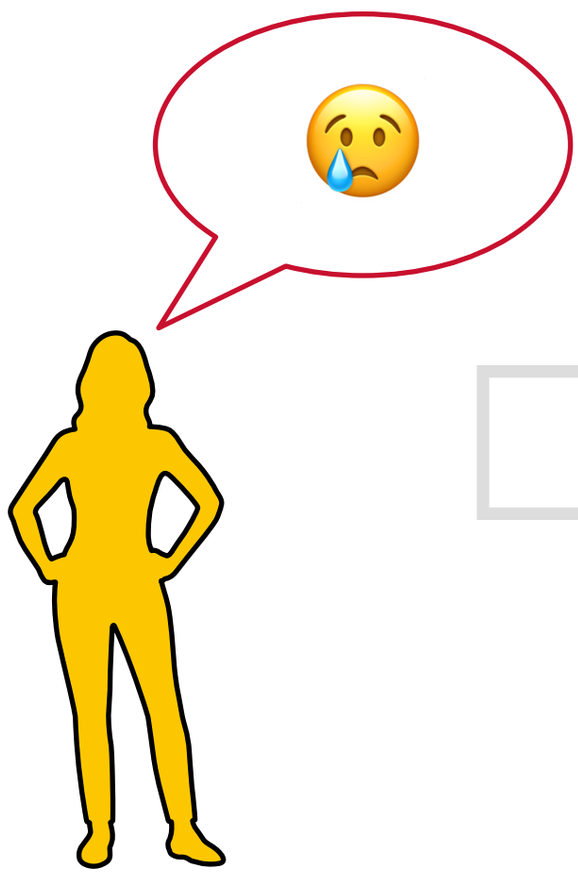

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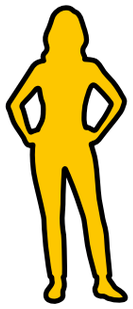
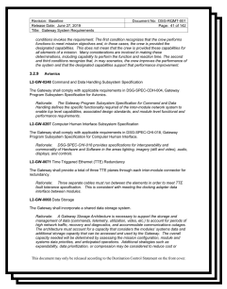
Patterns in Sam's Requirements





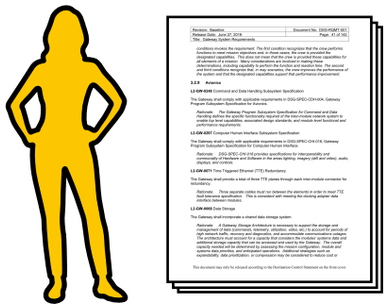
"Each request in the queue shall…"

"All active sensors shall…"

"Every task in the scheduler shall execute within 3 seconds"

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Patterns in Sam's Requirements



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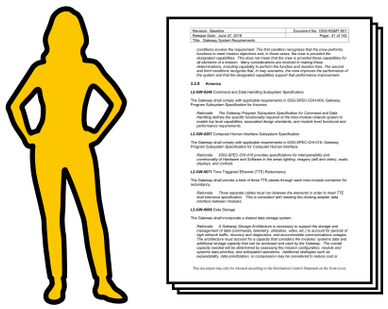
- **Guarded quantifiers:**

$$\forall x : Set(x) \rightarrow \Phi$$

$$\exists x : Set(x) \wedge \Phi$$

Patterns in Sam's Requirements



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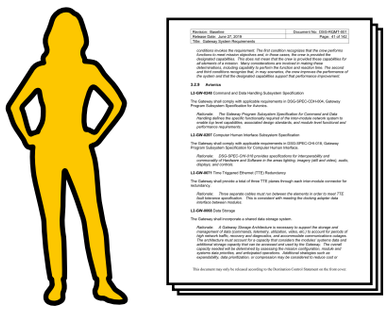
- **Bounded Dynamic Set**: A set that changes over time and has a bounded cardinality

Patterns in Sam's Requirements



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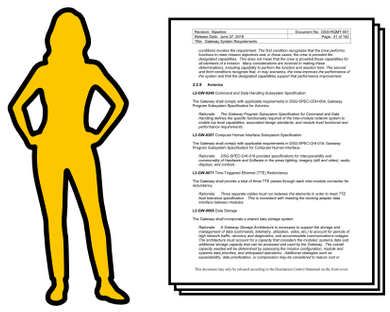
- **Bounded Dynamic Set**: A set that changes over time and has a bounded cardinality

Patterns in Sam's Requirements



"Each request in the **queue** shall…"

"All **active sensors** shall…"

"**Every task in the scheduler shall execute within 3 seconds**"

Require

$|Sched| \leq max(Sched)$

$$\square \; \forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

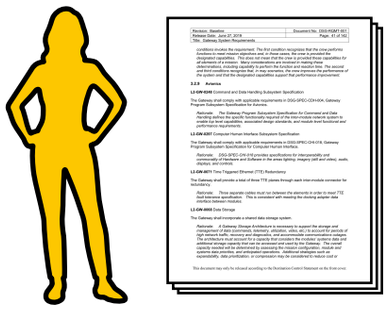
- **Guarded quantifiers:**

$$\forall x : Set(x) \rightarrow \Phi$$

$$\exists x : Set(x) \wedge \Phi$$

- **Bounded Dynamic Set**: A set that changes over time and has a bounded cardinality

Patterns in Sam's Requirements



"Each request in the **queue** shall…"

"All **active sensors** shall…"

"Every task in the scheduler shall execute within 3 seconds"

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

- **Guarded quantifiers:** $\forall x : Set(x) \rightarrow \Phi$ $\quad \exists x : Set(x) \wedge \Phi$
- **Bounded Dynamic Set**: A set that changes over time and has a bounded cardinality

$= \overline{\text{FO-MLTL}}$

FO-MLTL Quantifier Elimination

$$\cancel{\forall} t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$\bigwedge_{i \in [0,\ max(Sched)-1]} (Sched(t_i) \rightarrow \Diamond_{[0,3]} Exec(t_i))$$

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$\bigwedge_{i \in [0,\ max(Sched)-1]} (Sched(t_i) \rightarrow \Diamond_{[0,3]} Exec(t_i))$$

$$\wedge\ |Sched| \leq max(Sched)$$

Cardinality Constraint

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$\bigwedge_{i \in [0,\ max(Sched)-1]} (Sched(t_i) \rightarrow \Diamond_{[0,3]} Exec(t_i))$$

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$
$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

$$max(Sched) = 2$$

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$
$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Need to assign meaning

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$
$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

Arbitrarily assign

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Sched: A

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

Always False

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

Vacuously True

Sched: 

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

Vacuously True

Sched: 

Changes over time

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

	0	1	2	3	4
Sched					

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

	0	1	2	3	4
Sched	■■	■■	■■	■■	■■

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$
$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$
$$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$$
$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$
$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Instantiate

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$

$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

...

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Instantiate

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$

$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$
$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$

...

MLTL Monitors (.bin **)**

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$$

$$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

Instantiate

How many?

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$

$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

...

MLTL Monitors (.bin **)**

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll **Will know answer by time 3**

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$
$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

	0	1	2	3	4
Sched	A	A B		C	D E

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$

$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot)) \wedge$
$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot))$

$(Sched(\bot) \rightarrow \Diamond_{[0,3]} Exec(\bot)) \wedge$
$(Sched(C) \rightarrow \Diamond_{[0,3]} Exec(C))$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$$

$$(Sched(C) \rightarrow \Diamond_{[0,3]} Exec(C))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

Re-use this space!

$$[Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$

$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge$
$(Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$

$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$
$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$

$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge$
$(Sched(C) \rightarrow \Diamond_{[0,3]} Exec(C))$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

Unroll

Re-use this space!

Only need space for 4 formulas

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge (Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

$$(Sched(A) \rightarrow \Diamond_{[0,3]} Exec(A)) \wedge (Sched(B) \rightarrow \Diamond_{[0,3]} Exec(B))$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge (Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp))$$

$$(Sched(\perp) \rightarrow \Diamond_{[0,3]} Exec(\perp)) \wedge (Sched(C) \rightarrow \Diamond_{[0,3]} Exec(C))$$

$$(Sched(D) \rightarrow \Diamond_{[0,3]} Exec(D)) \wedge (Sched(E) \rightarrow \Diamond_{[0,3]} Exec(E))$$

	0	1	2	3	4
Sched	A	A B		C	D E

FO-MLTL **Quantifier Elimination**

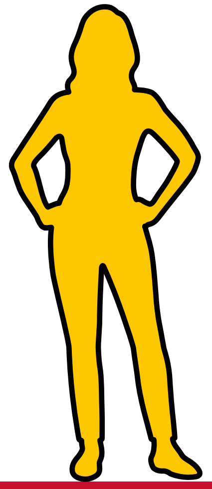
$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \land (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \land (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \land (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$

$$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \land (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$$



FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

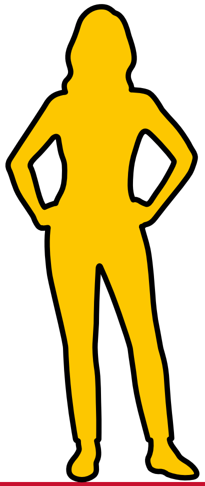
$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$
$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$

$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$
$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$

$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$
$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$

$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$
$(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$

(Quantifier-free) MLTL formulas

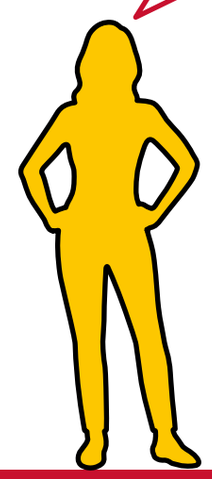


FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$ $(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$	$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$ $(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$	$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$ $(Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$	$(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge$ $(Sched(t_1)$

Yay!



(Quantifier-free) MLTL formulas

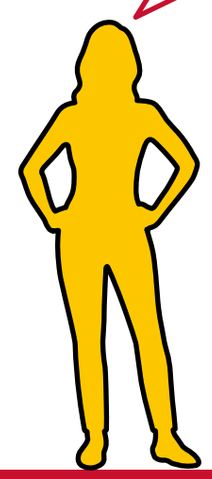
Can monitor using R2U2!

FO-MLTL Quantifier Elimination

$$\forall t : Sched(t) \rightarrow \Diamond_{[0,3]} Exec(t)$$

- $(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$
- $(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$
- $(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge (Sched(t_1) \rightarrow \Diamond_{[0,3]} Exec(t_1))$
- $(Sched(t_0) \rightarrow \Diamond_{[0,3]} Exec(t_0)) \wedge (Sched(t_1)$

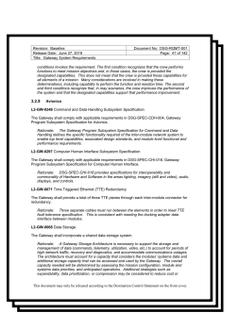
Yay!



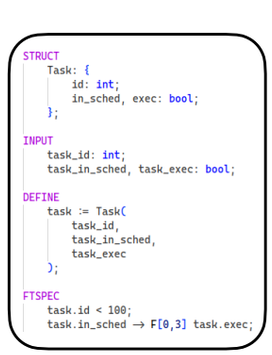
(Quantifier-free) MLTL formulas

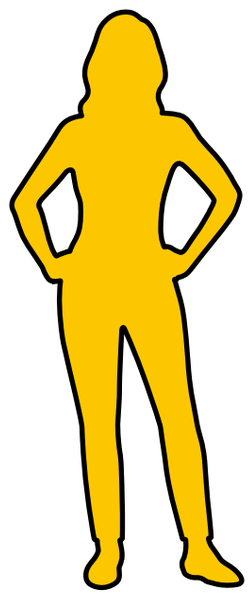
Can monitor using R2U2!***

R2U2 + C2PO Approach

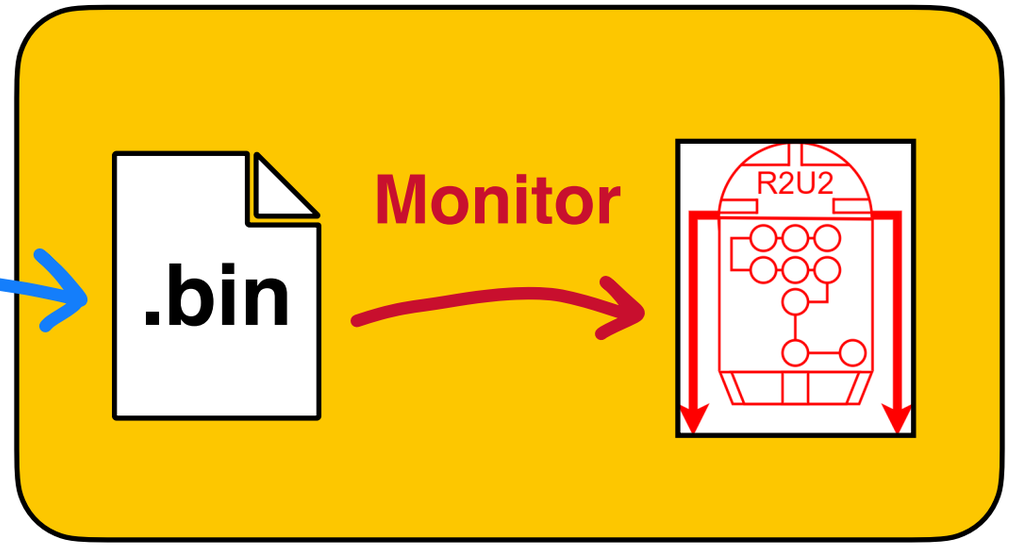


Formaliz

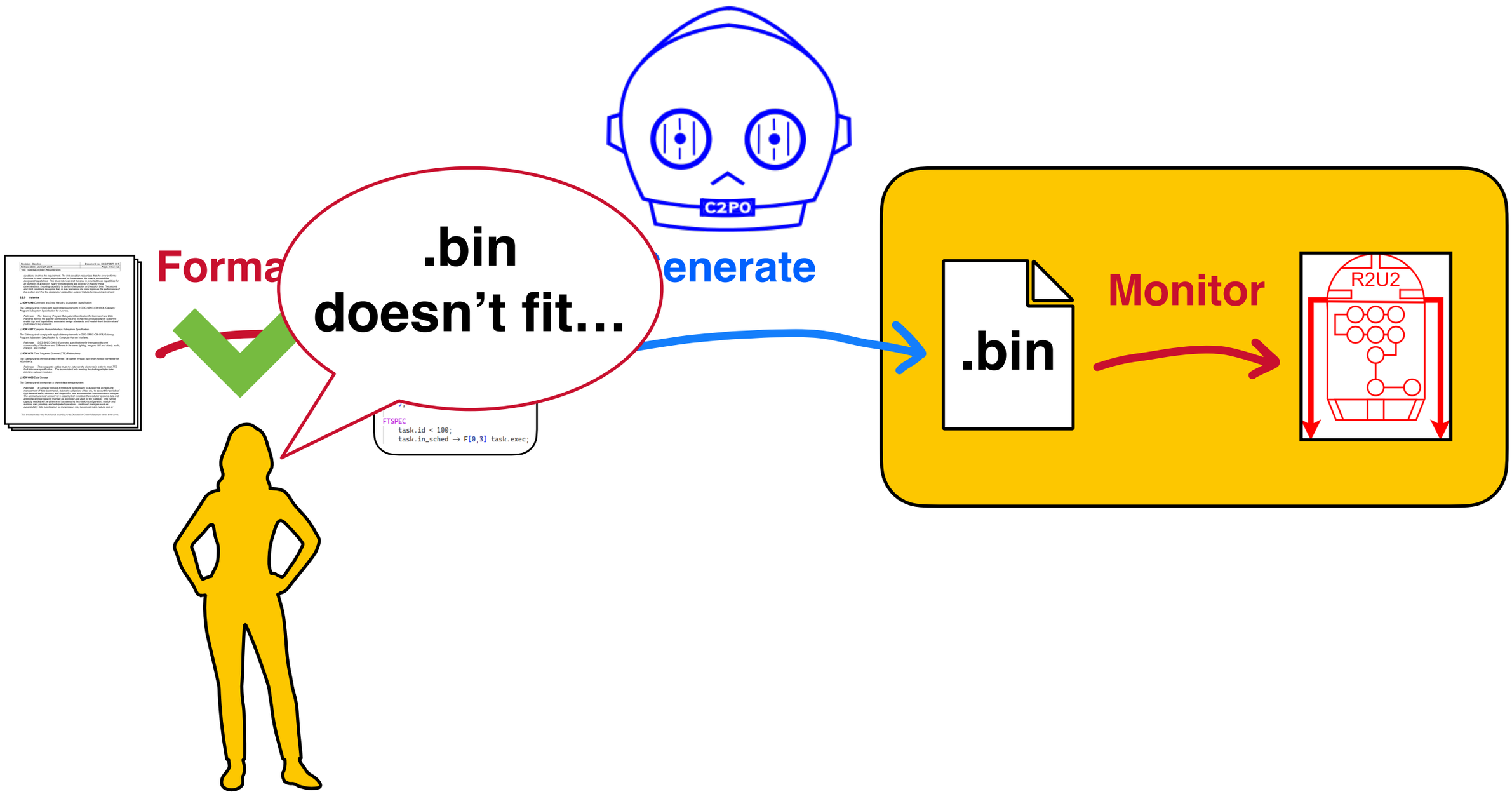




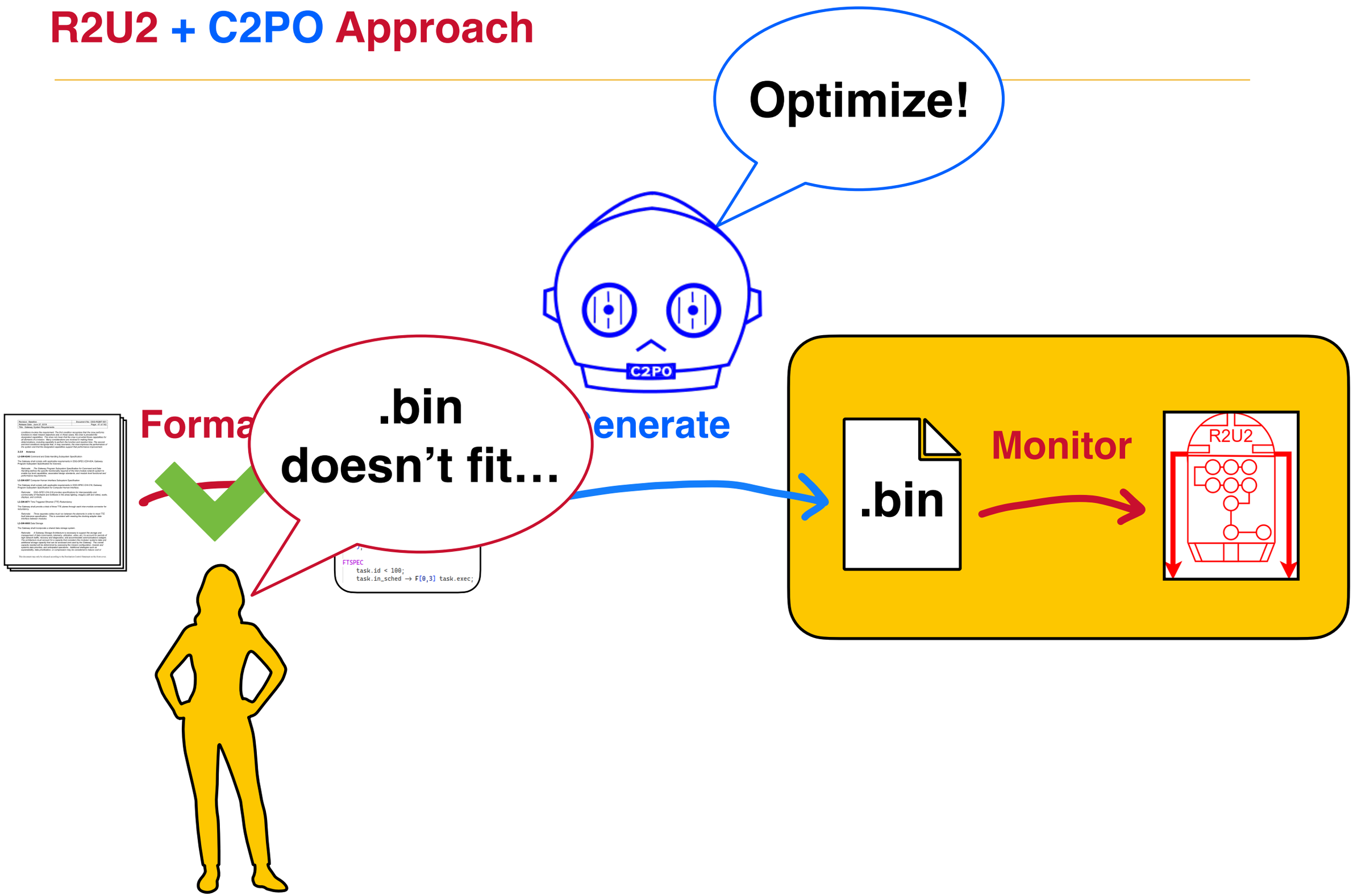
Generate



R2U2 + C2PO Approach

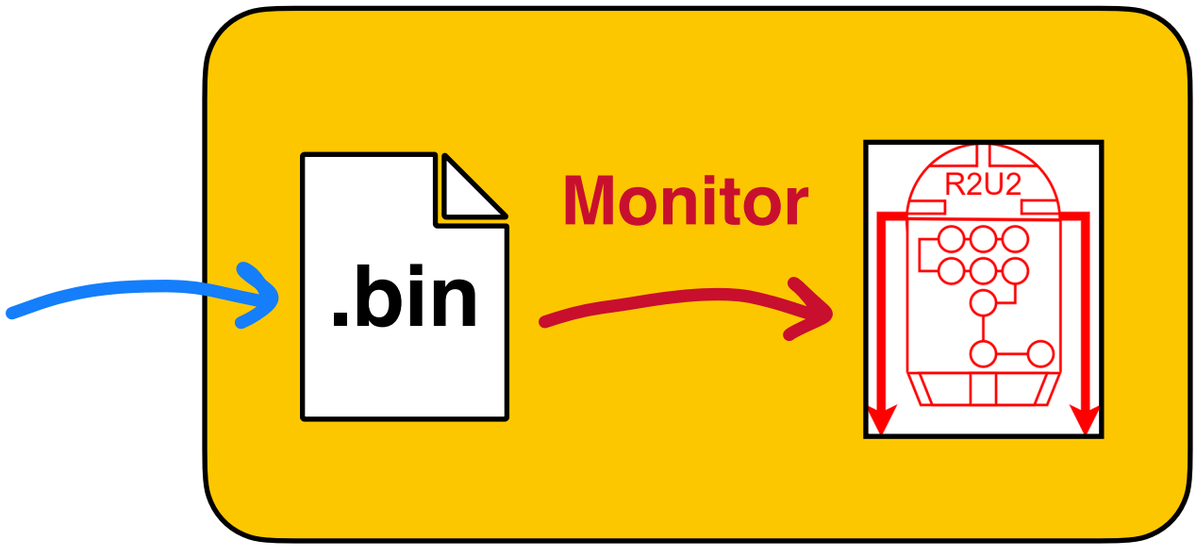


R2U2 + C2PO Approach



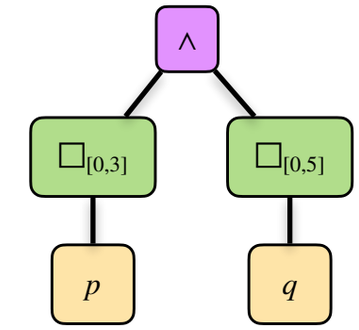
How does R2U2 Encode MLTL? [18]

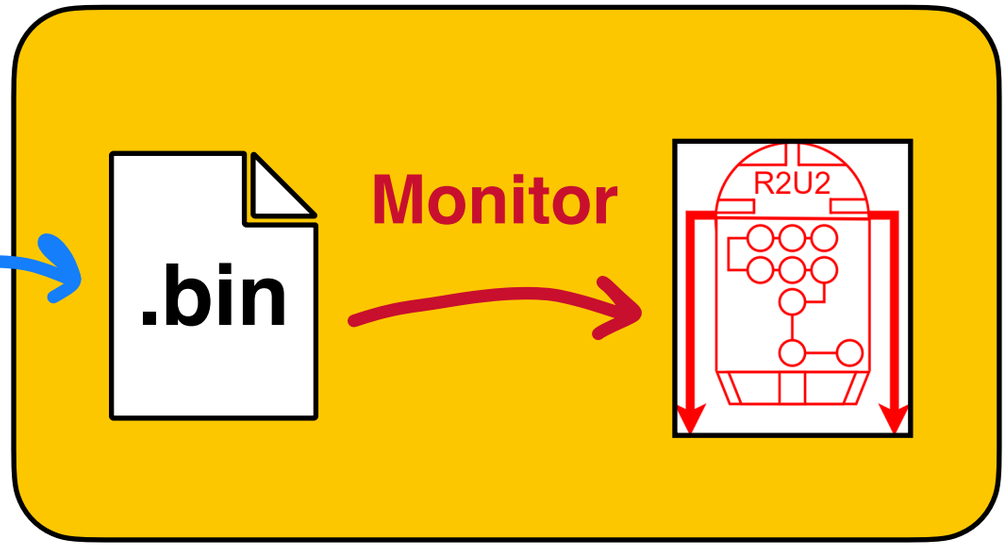
$$\square_{[0,3]}\, p \wedge \square_{[0,5]} q$$



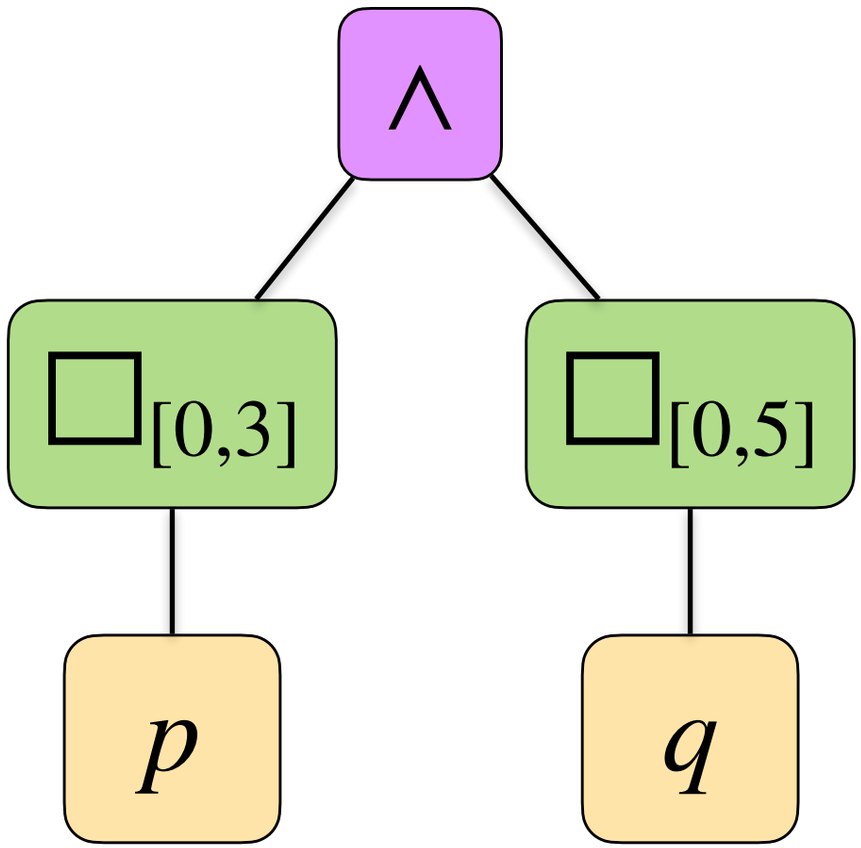
How does R2U2 Encode MLTL? [18]

$\square_{[0,3]}\, p \wedge \square_{[0,5]} q$

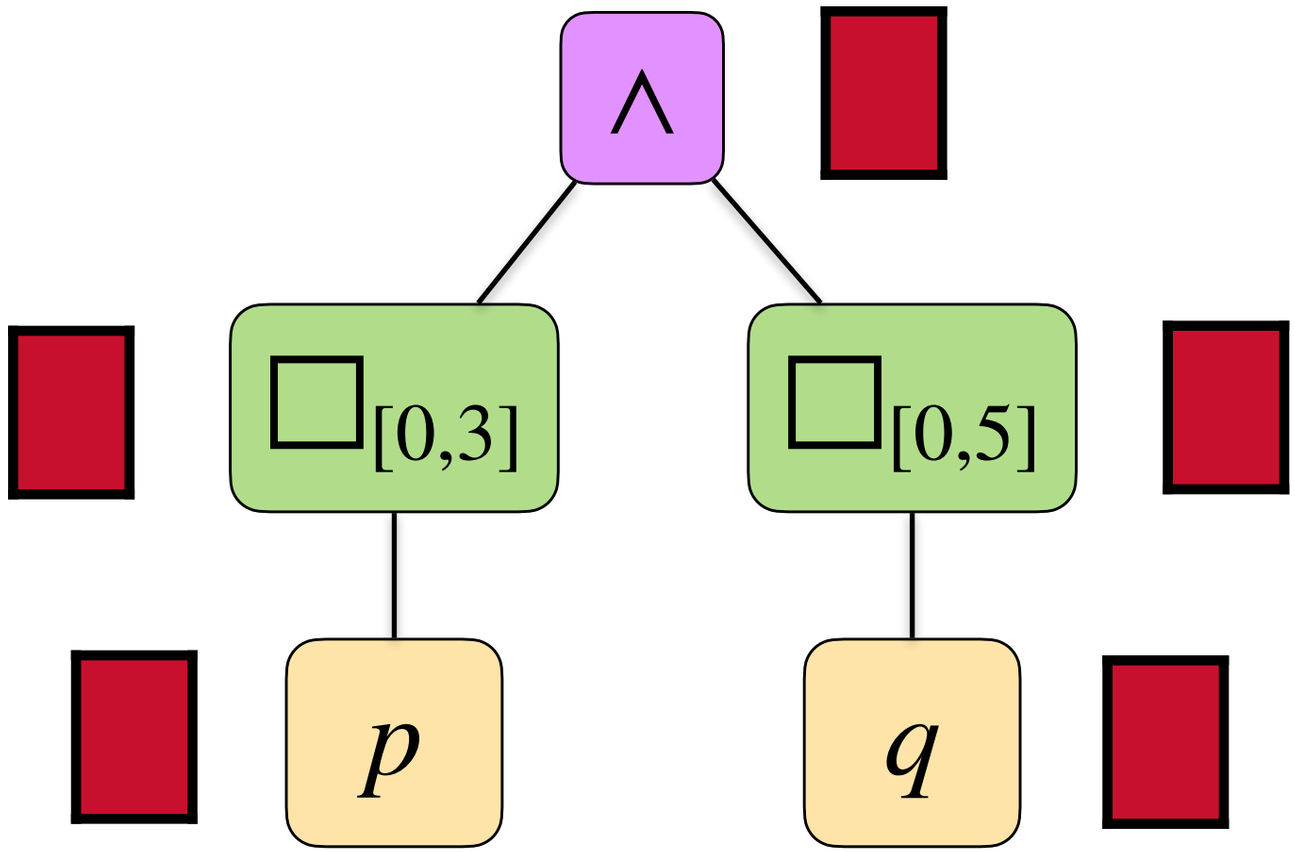




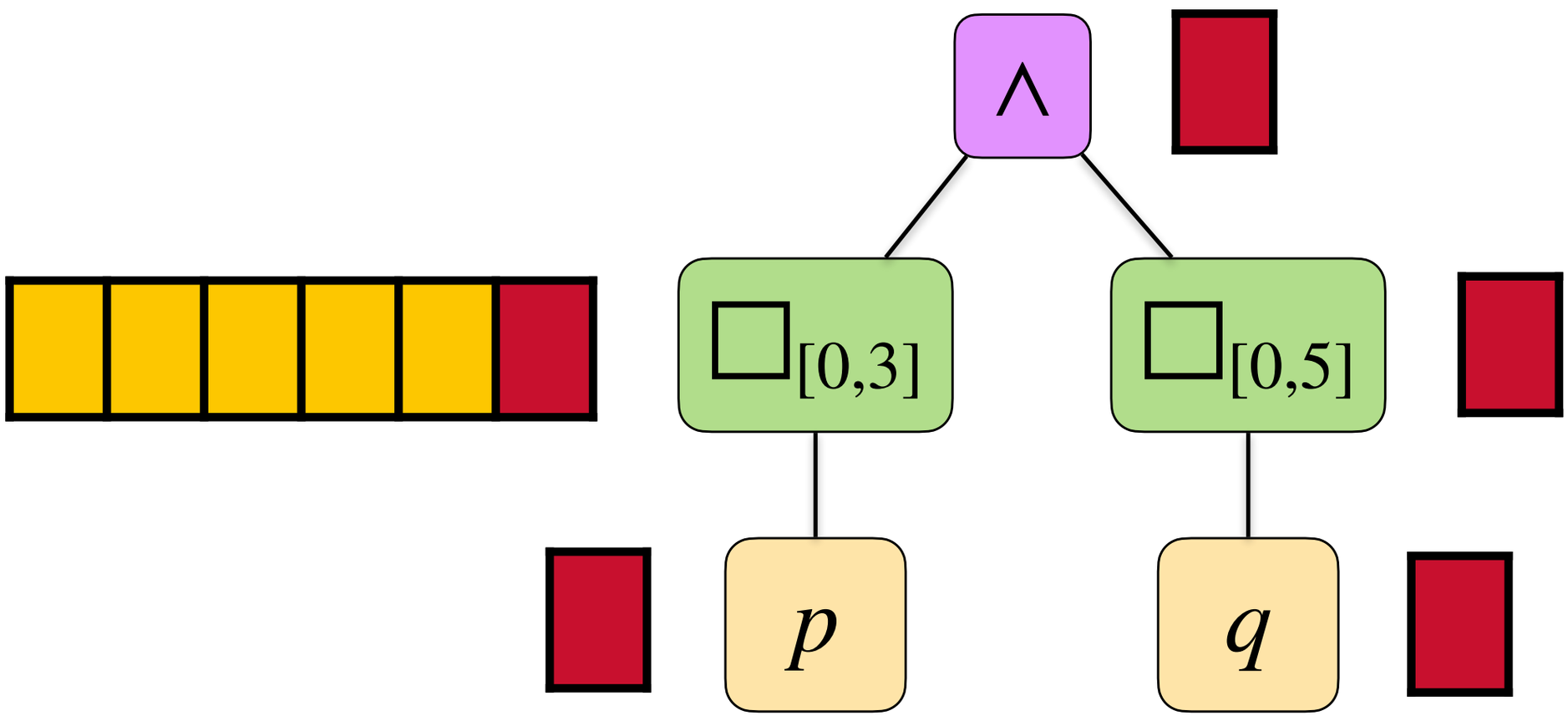
How does R2U2 Encode MLTL? [18]



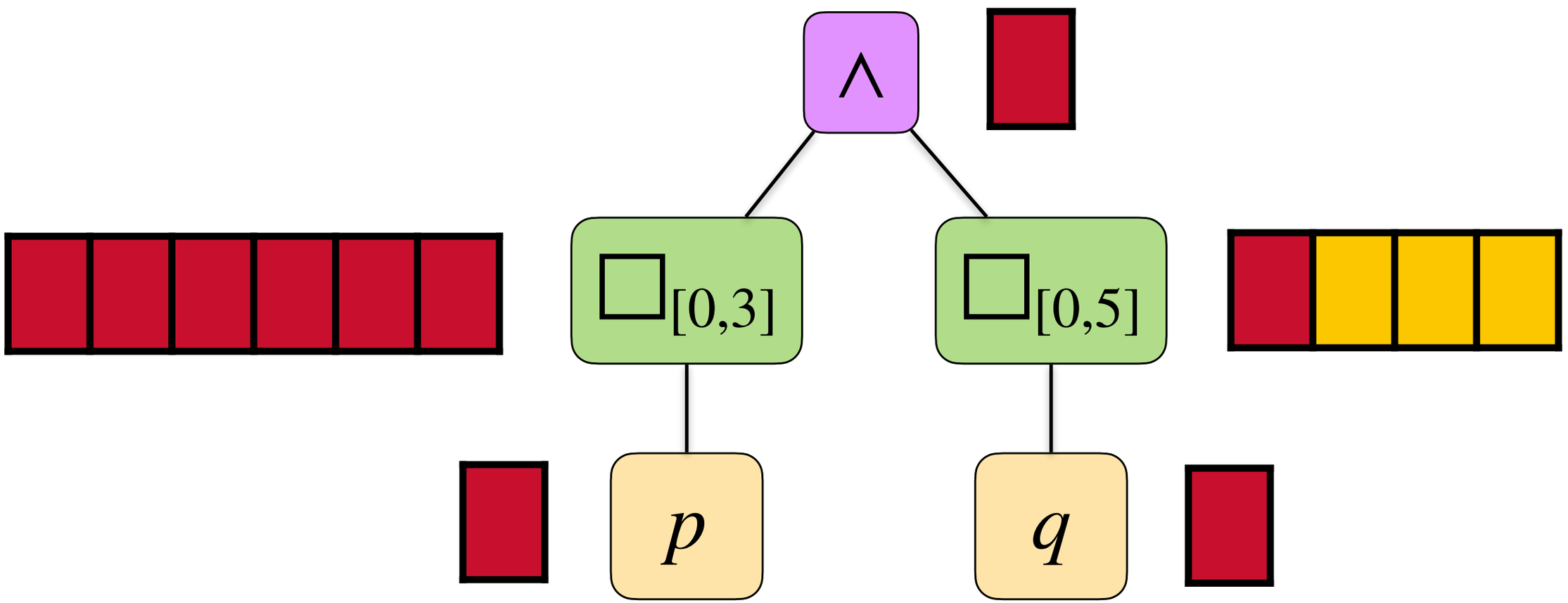
How does R2U2 Encode MLTL? [18]



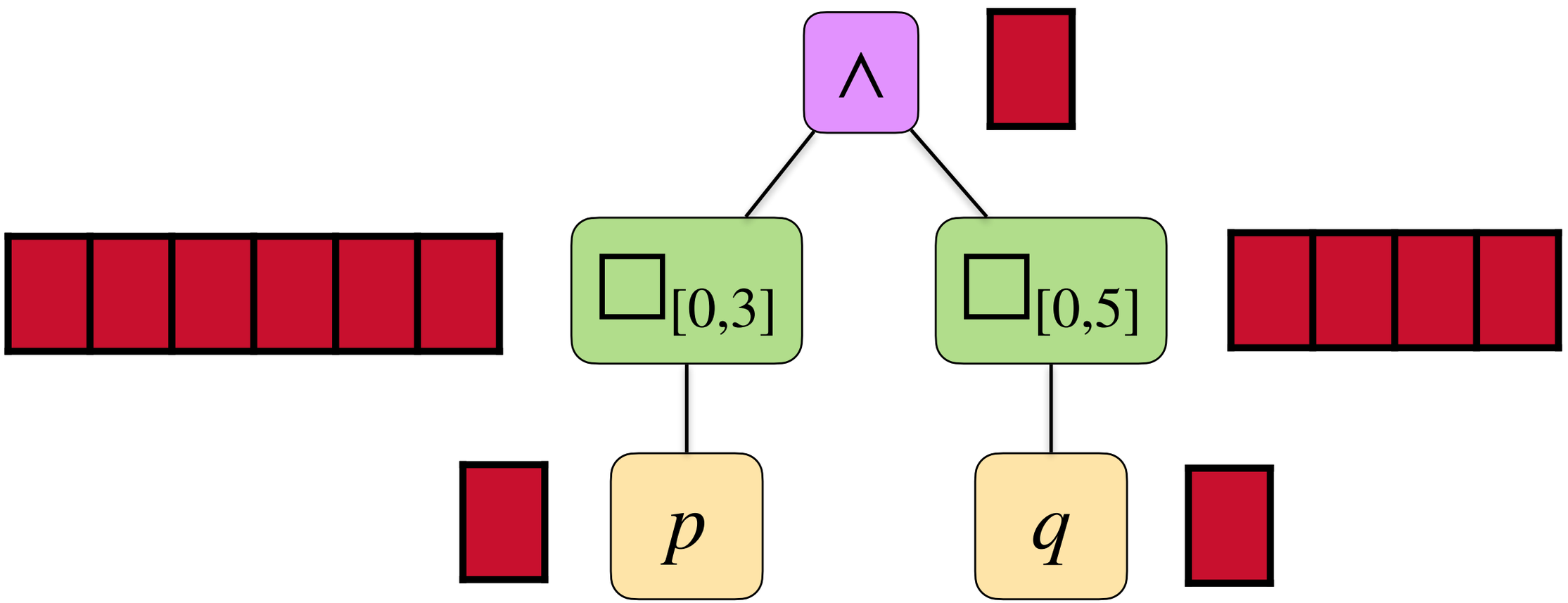
How does R2U2 Encode MLTL? [18]



How does R2U2 Encode MLTL? [18]



How does R2U2 Encode MLTL? [18]



| buffer | ∼ upper bounds of siblings

- **Reduce number of nodes**
- **Reduce sum of upper bounds**

MLTL Rewrite Rules

$$\square_{[0,3]} p \wedge \square_{[0,5]} q$$

MLTL Rewrite Rules

$$\square_{[0,3]} p \wedge \square_{[0,5]} q$$

Share the interval [0,3]

MLTL Rewrite Rules

$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$

$$\Rightarrow$$

$$\Box_{[0,3]} (\Box_{[0,0]} p \wedge \Box_{[0,2]} q)$$

Factor out common interval

MLTL Rewrite Rules

$$\square_{[0,3]} p \wedge \square_{[0,5]} q$$

$$\Rightarrow$$

$$\square_{[0,3]} (\square_{[0,0]} p \wedge \square_{[0,2]} q)$$

$$\square_{[0,0]} p \equiv p$$

MLTL Rewrite Rules

$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$

$$\Rightarrow$$

$$\Box_{[0,3]} (p \wedge \Box_{[0,2]} q)$$

MLTL Rewrite Rules

$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$

	0	1	2	3	4	5
p						
q						

$$=$$

$$\Box_{[0,3]} (p \wedge \Box_{[0,2]} q)$$

MLTL Rewrite Rules

$$\square_{[0,3]} p \wedge \square_{[0,5]} q$$

	0	1	2	3	4	5
p						
q						

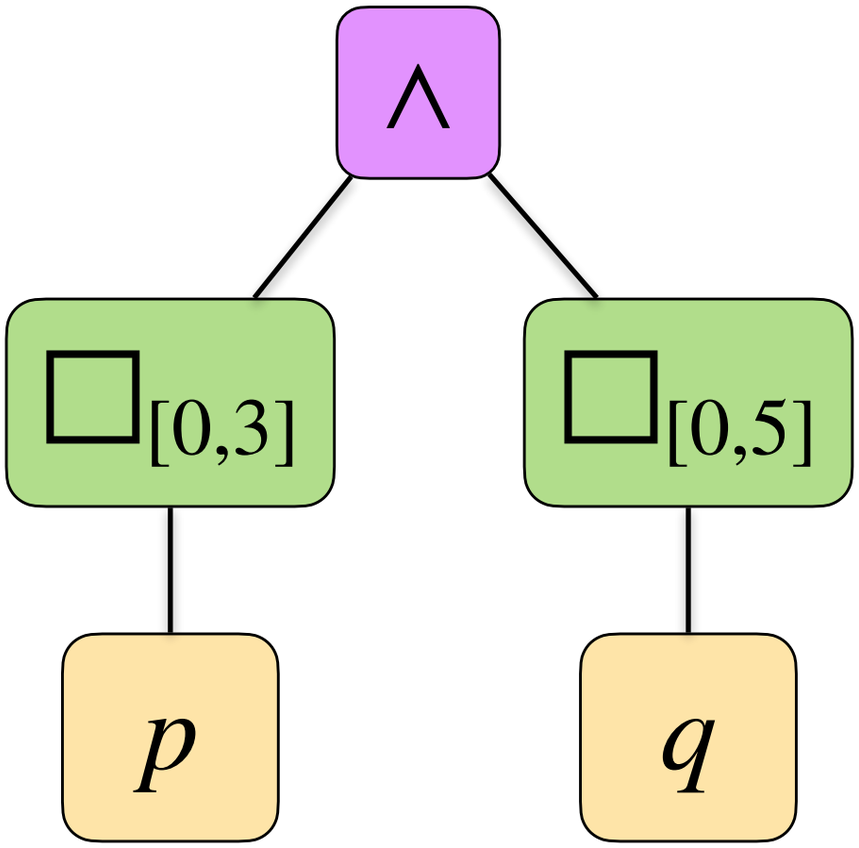
$$=$$

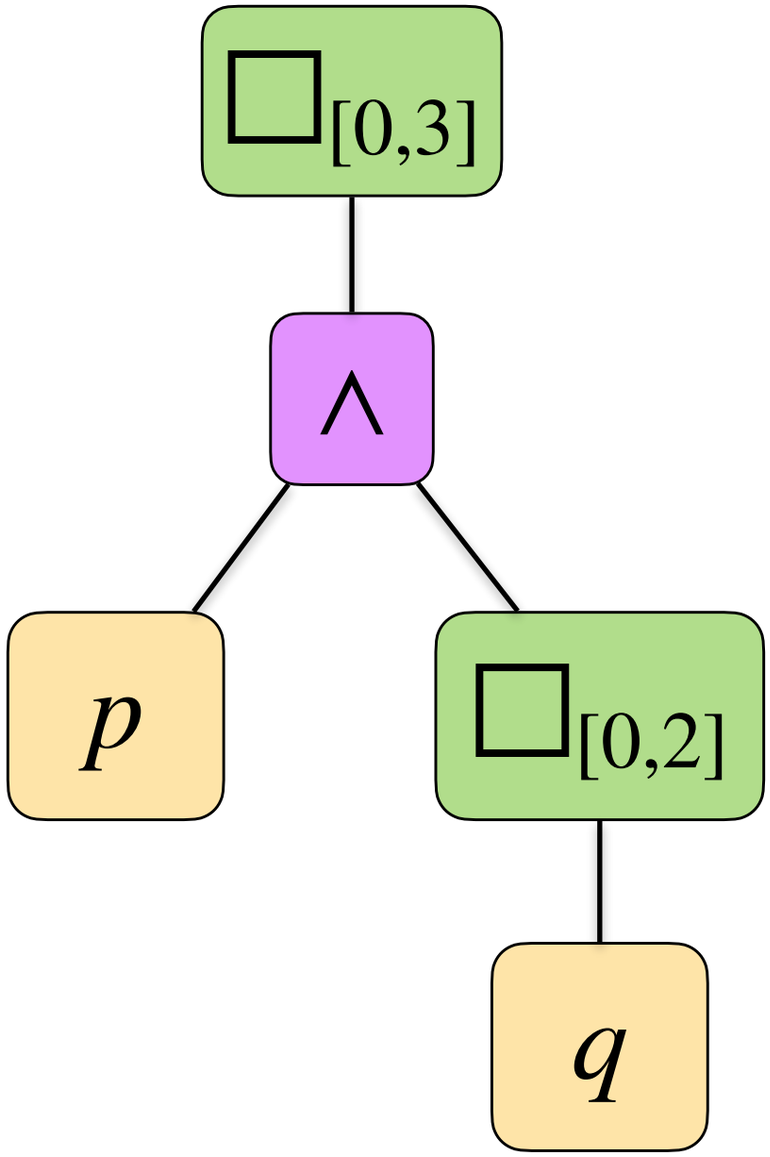
$$\square_{[0,3]} (p \wedge \square_{[0,2]} q)$$

	0	1	2	3	4	5
p						
q						

MLTL Rewrite Rules

$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q \quad \Rightarrow \quad \Box_{[0,3]} (p \wedge \Box_{[0,2]} q)$$





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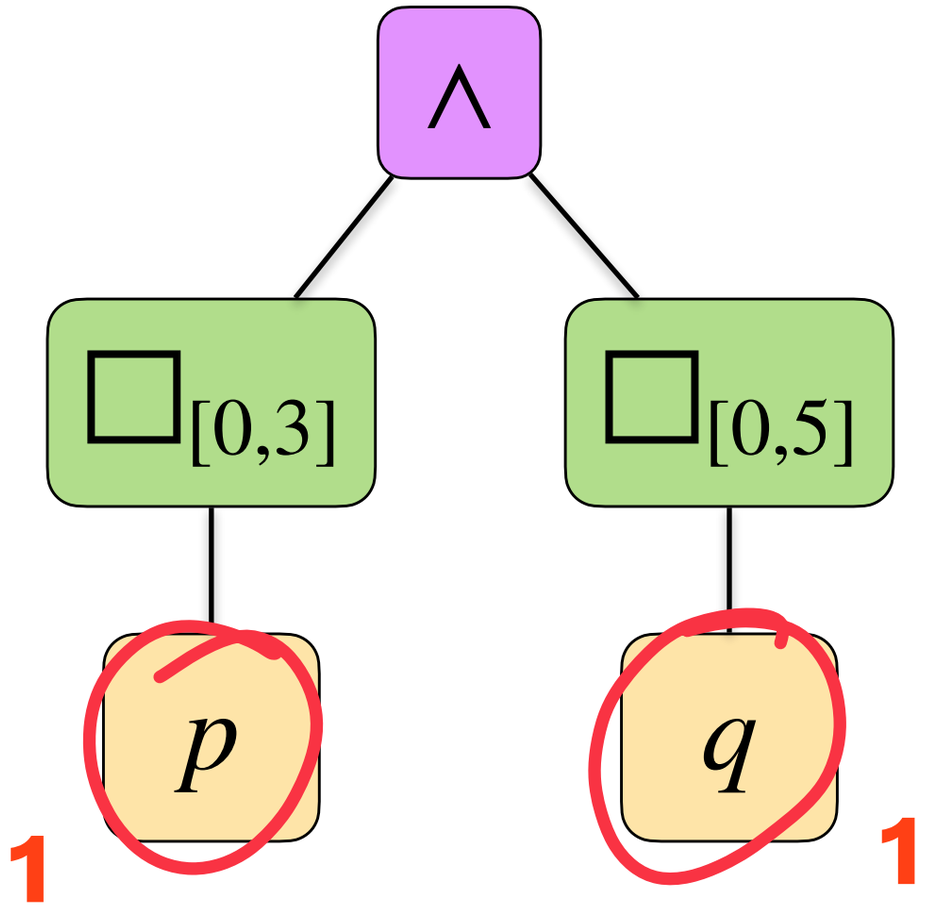

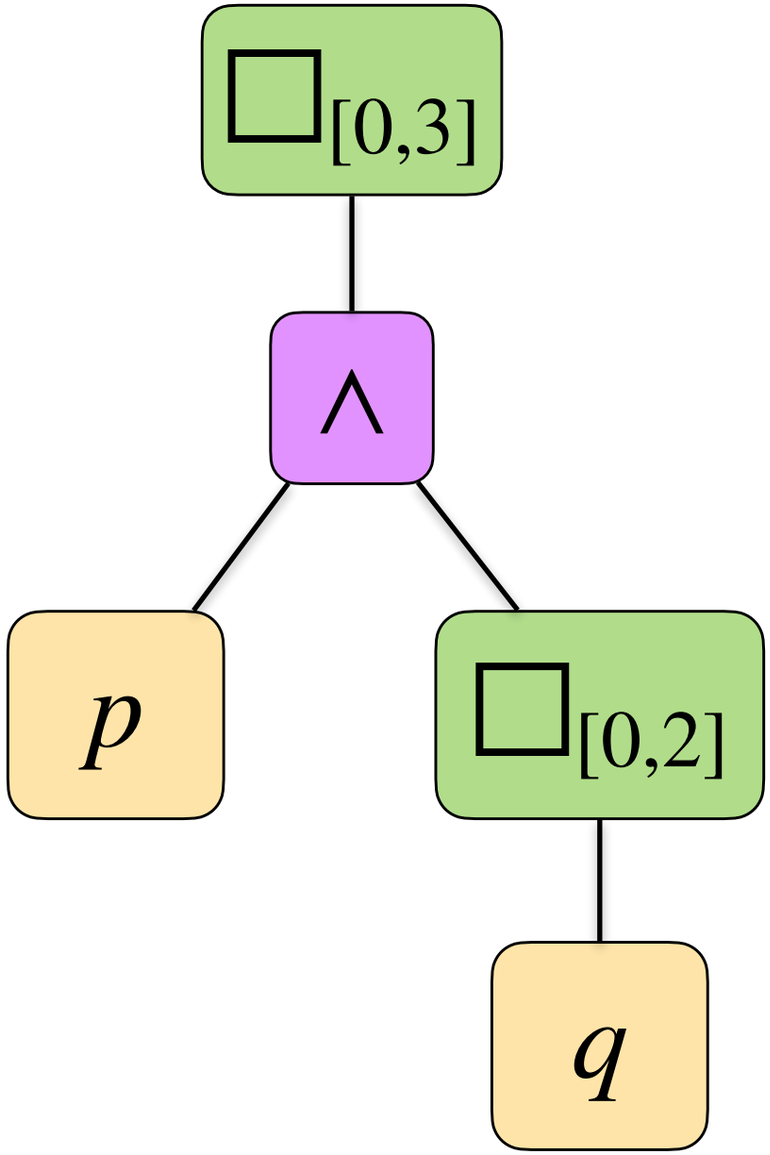

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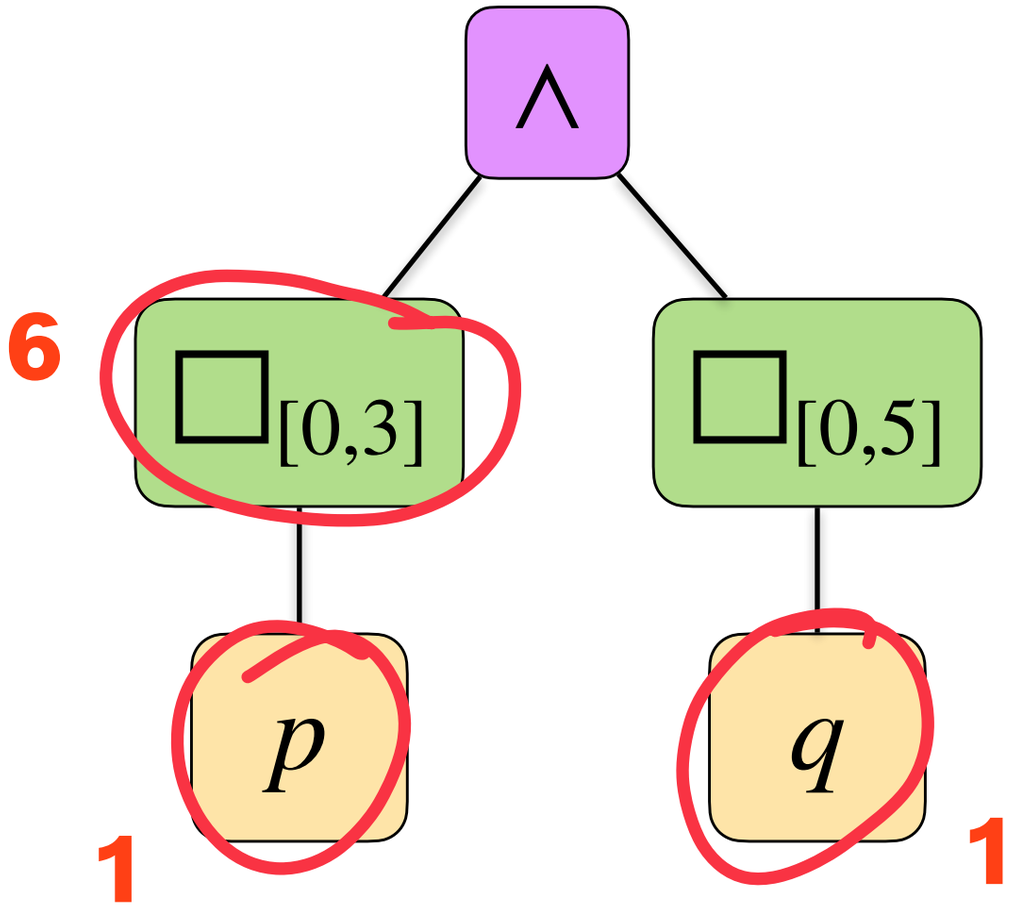

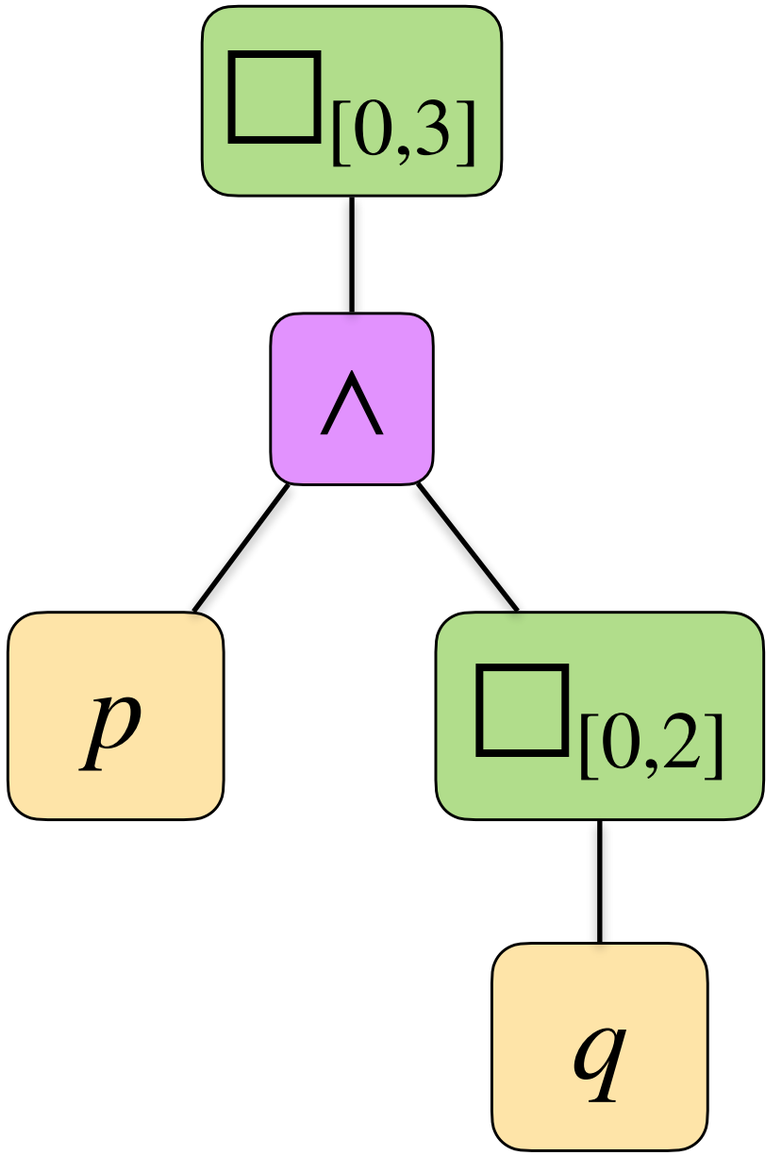

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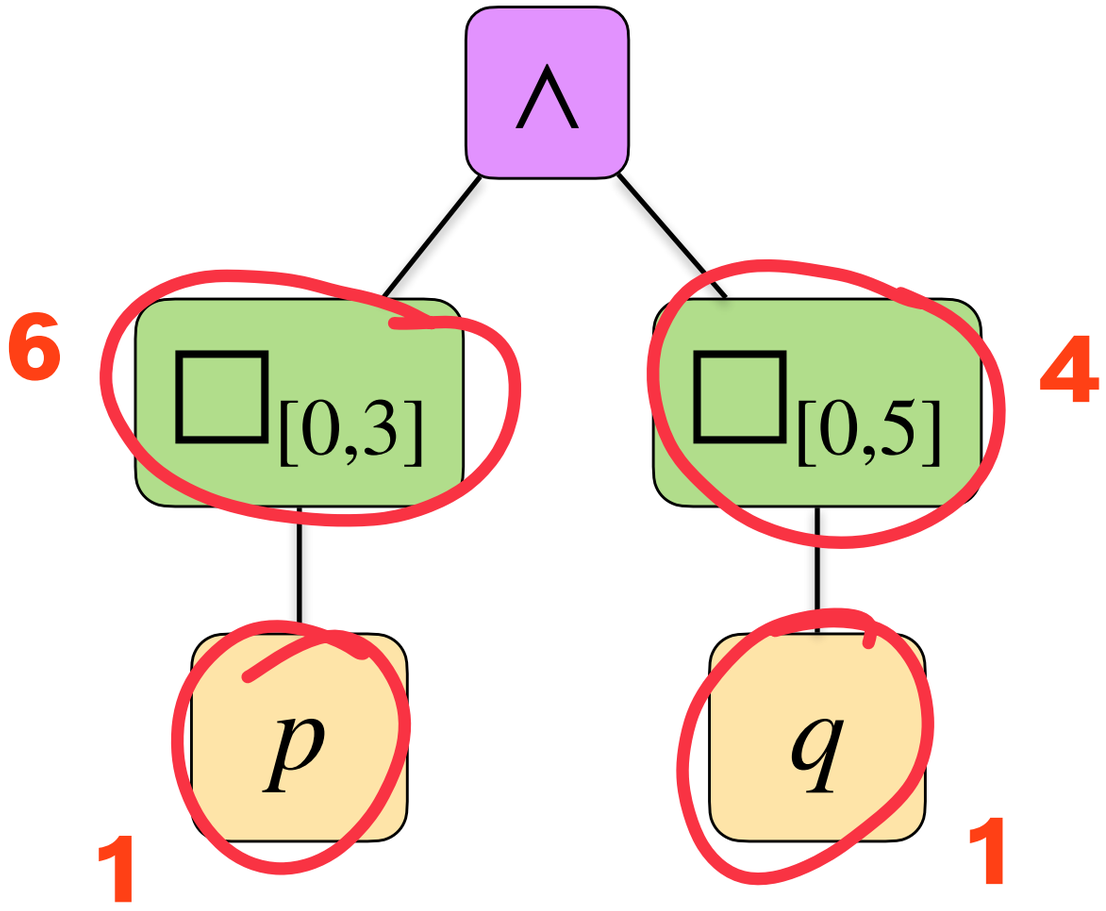

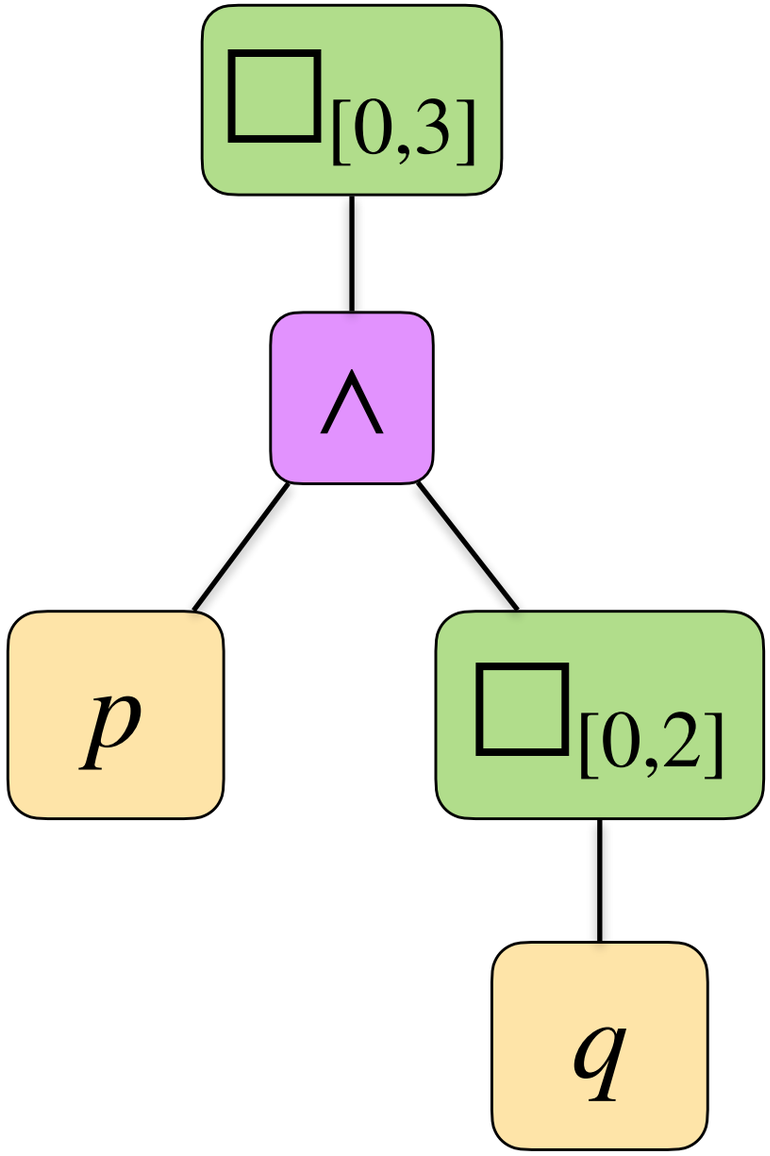

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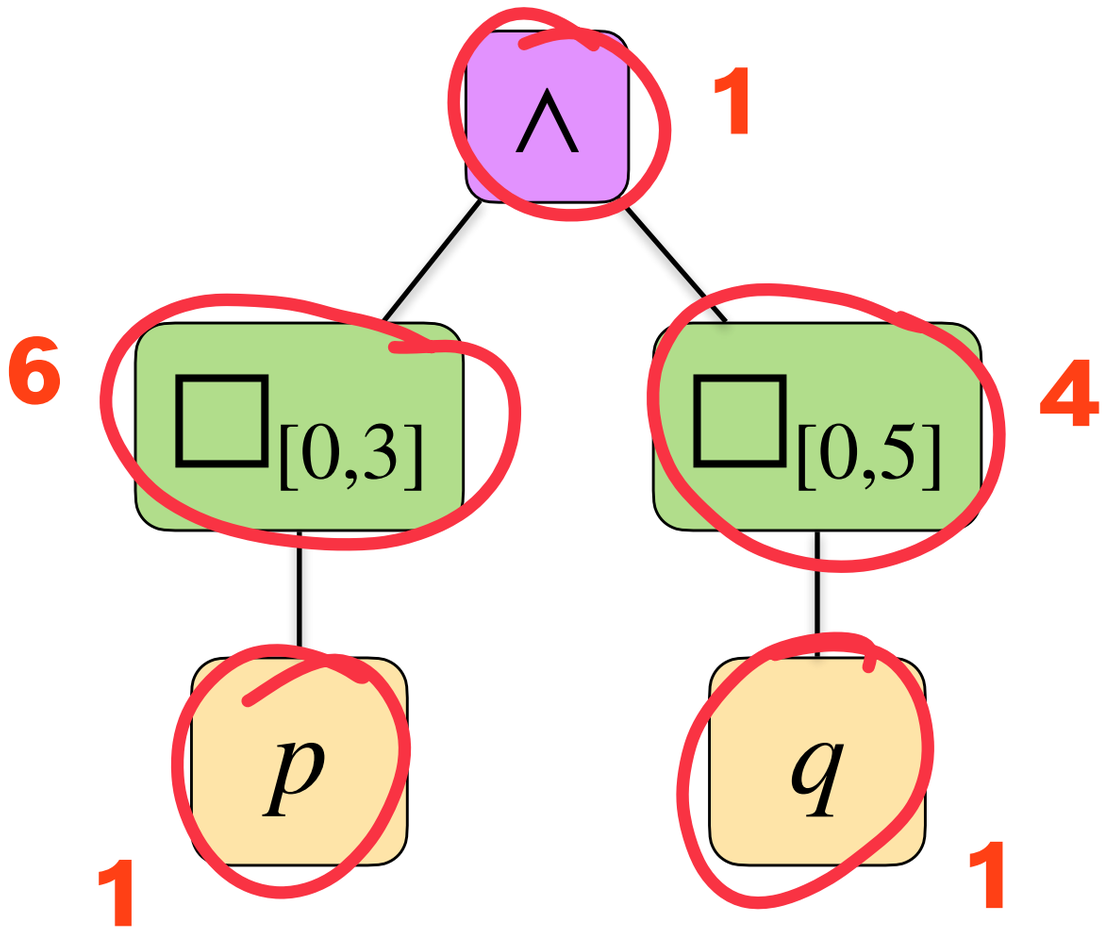

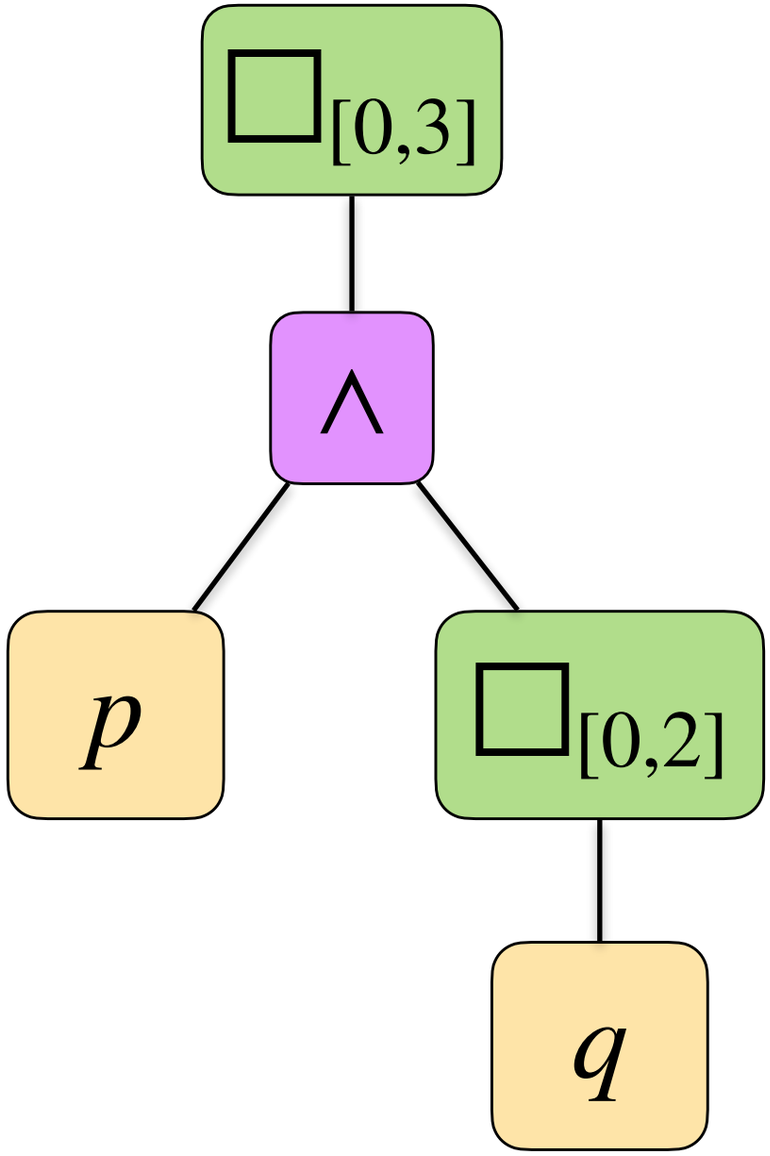

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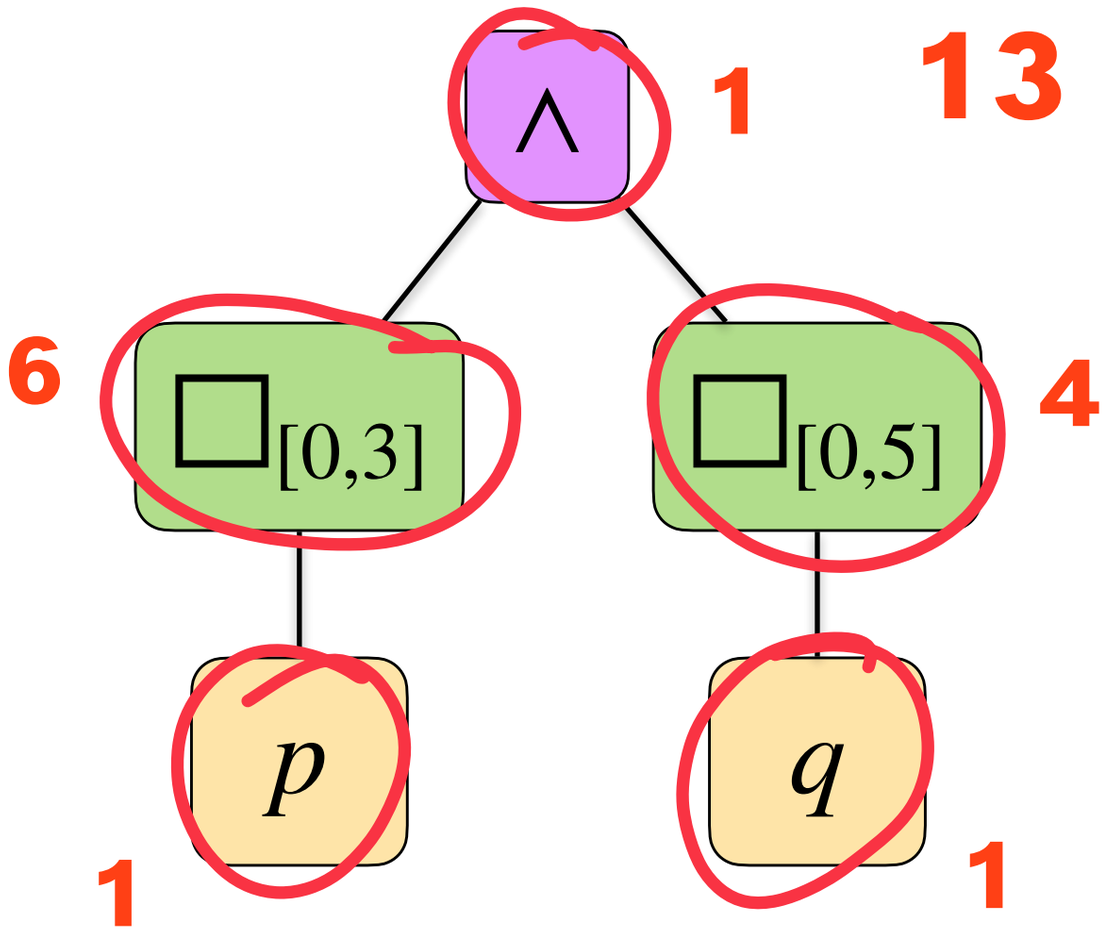

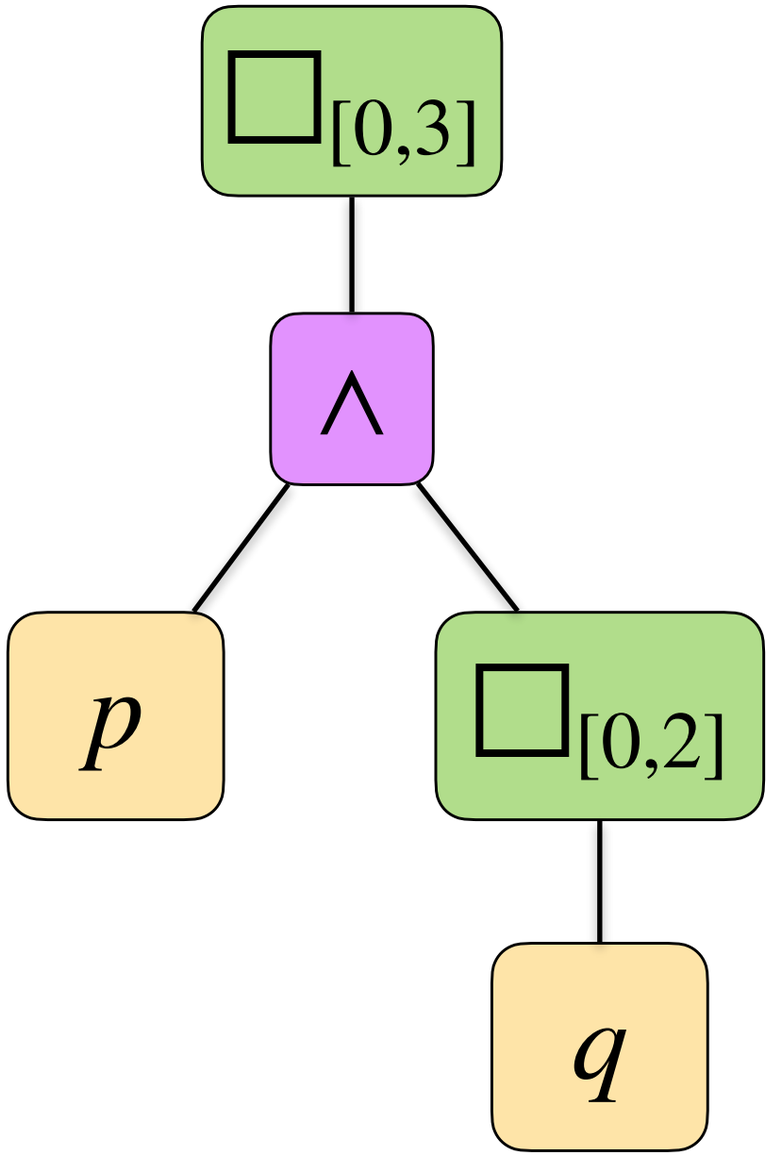

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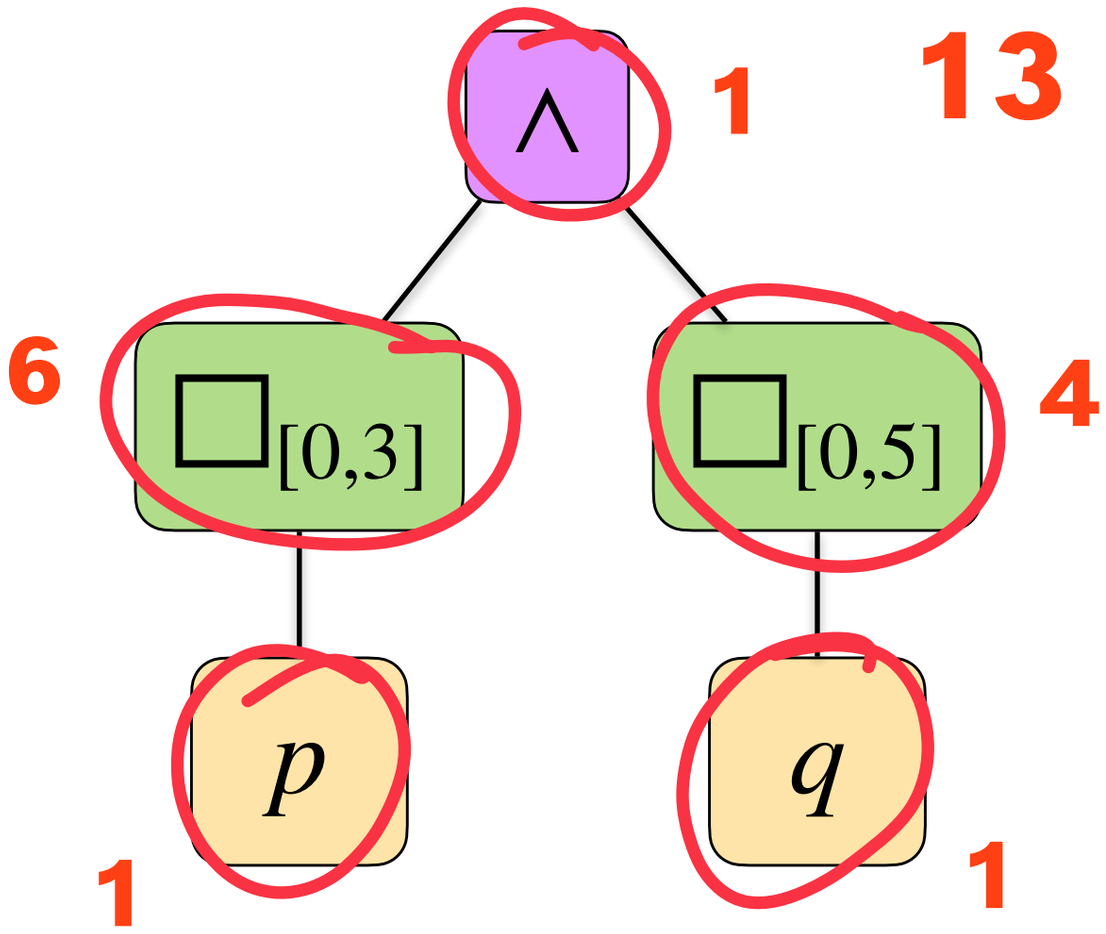

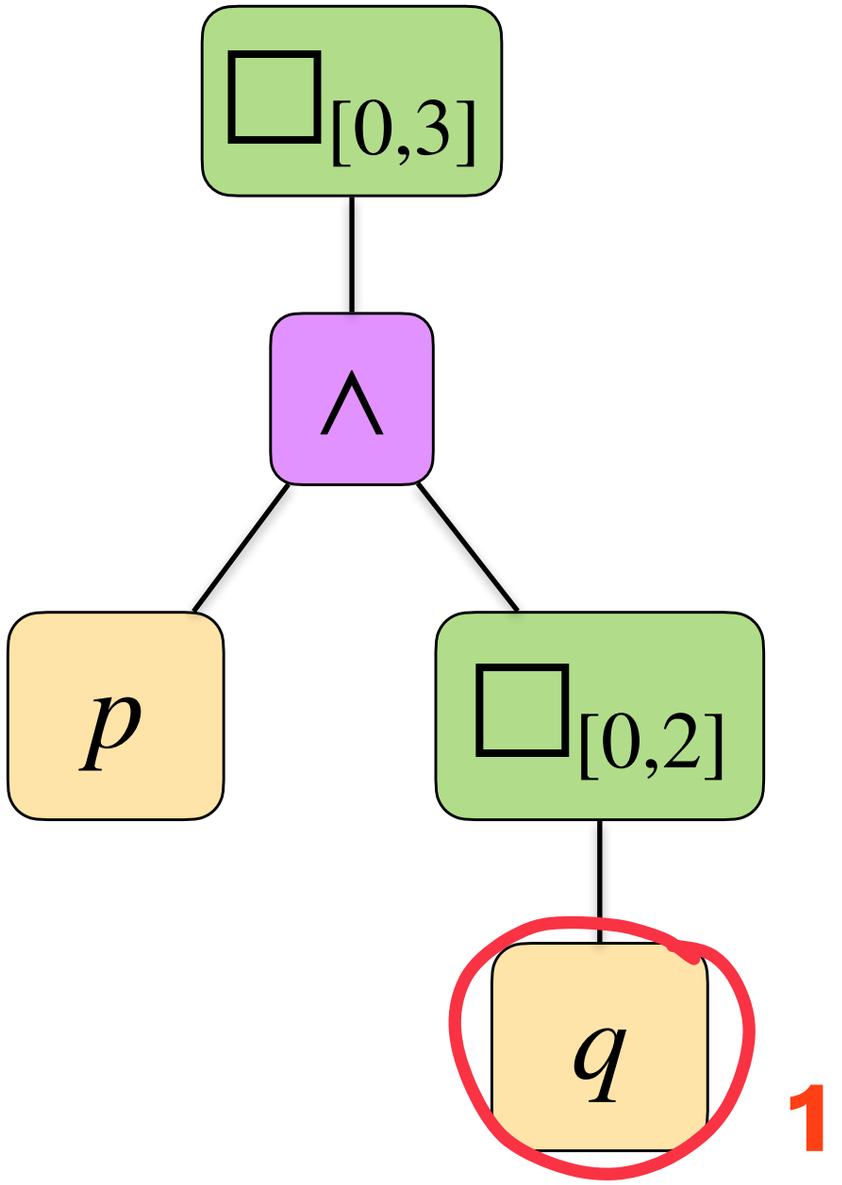

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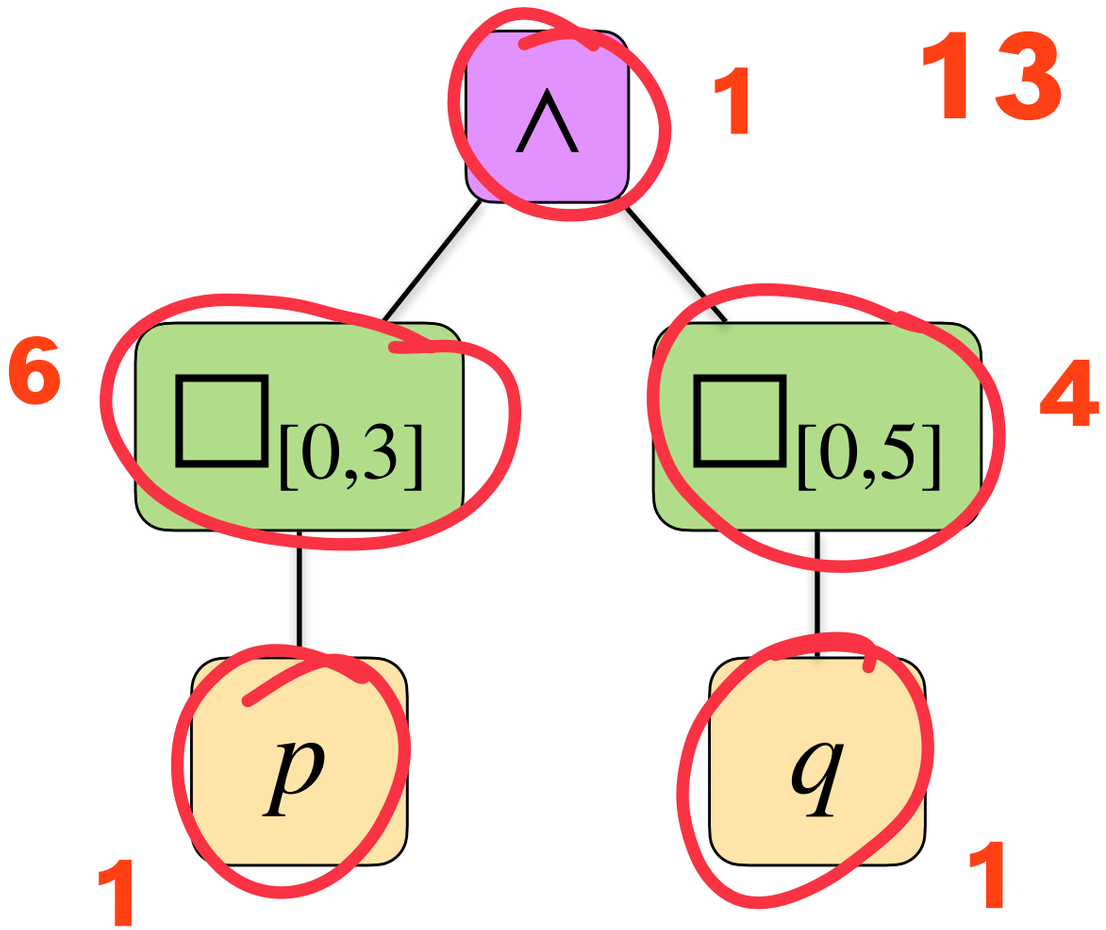

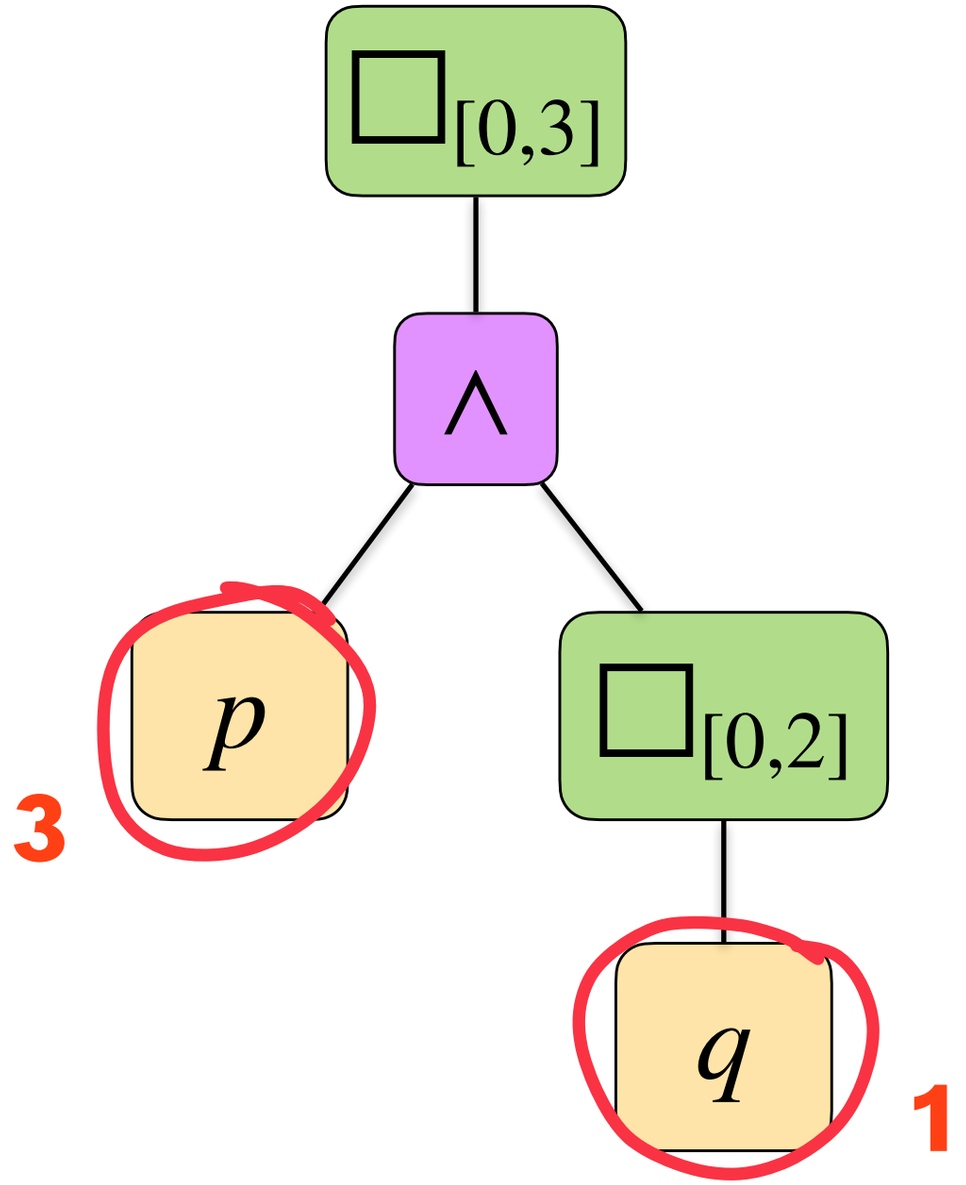

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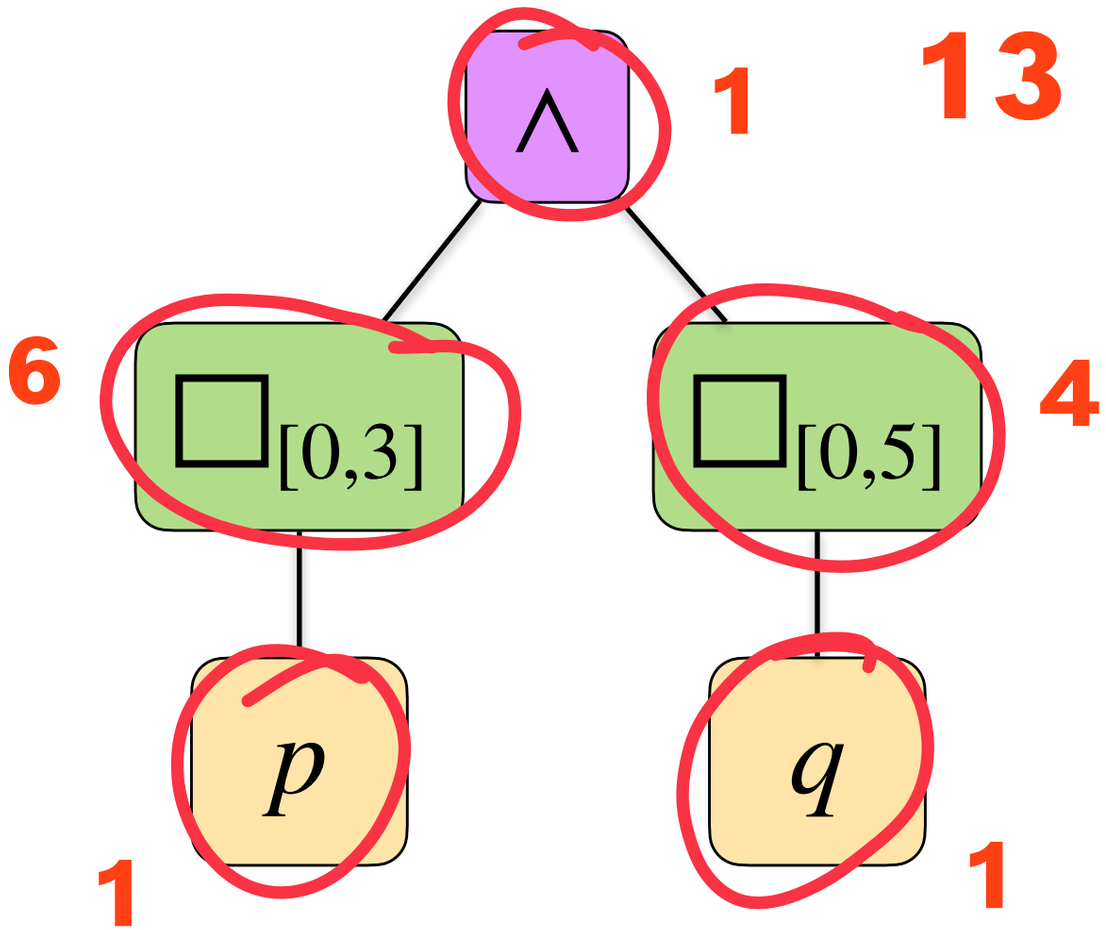

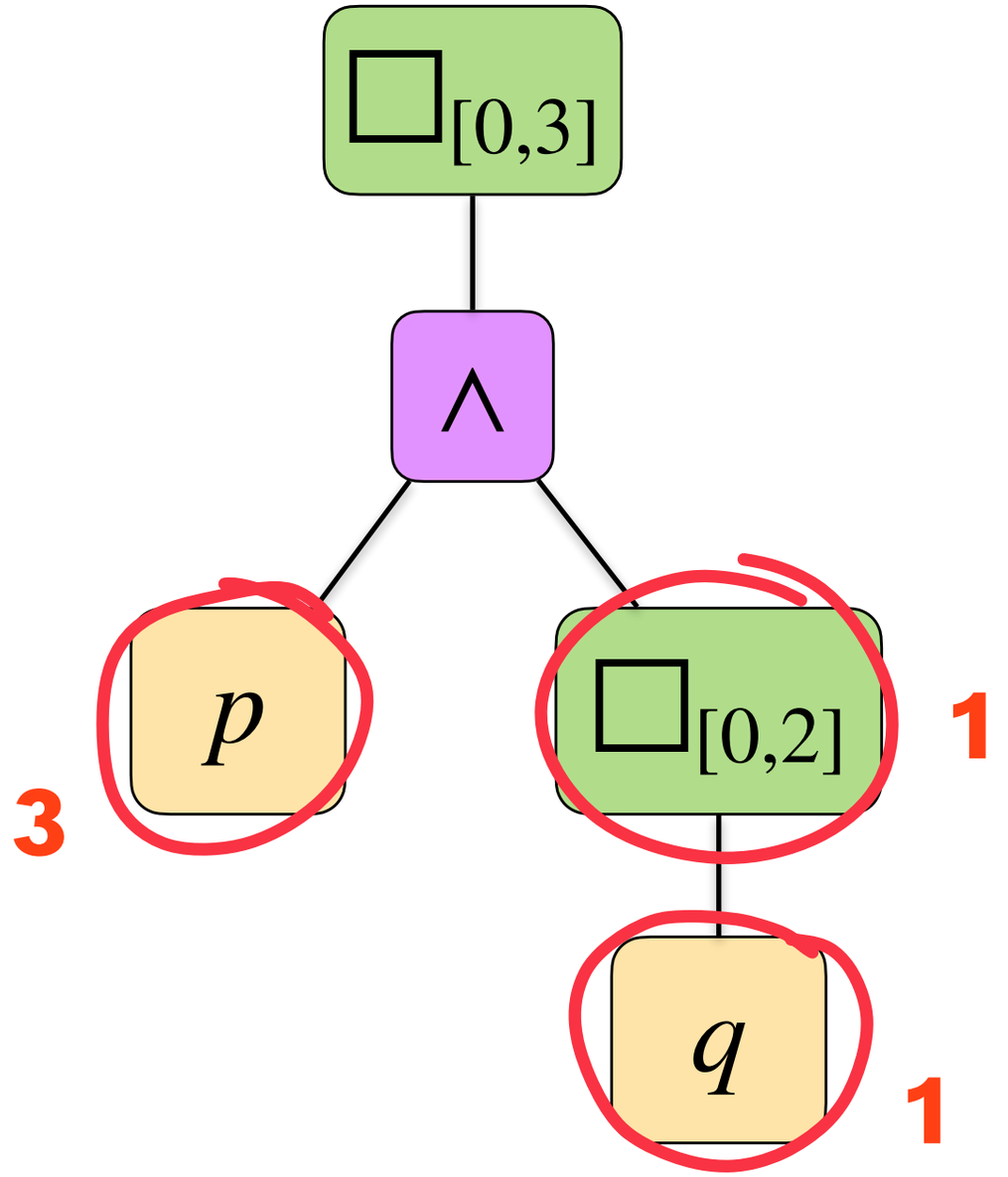

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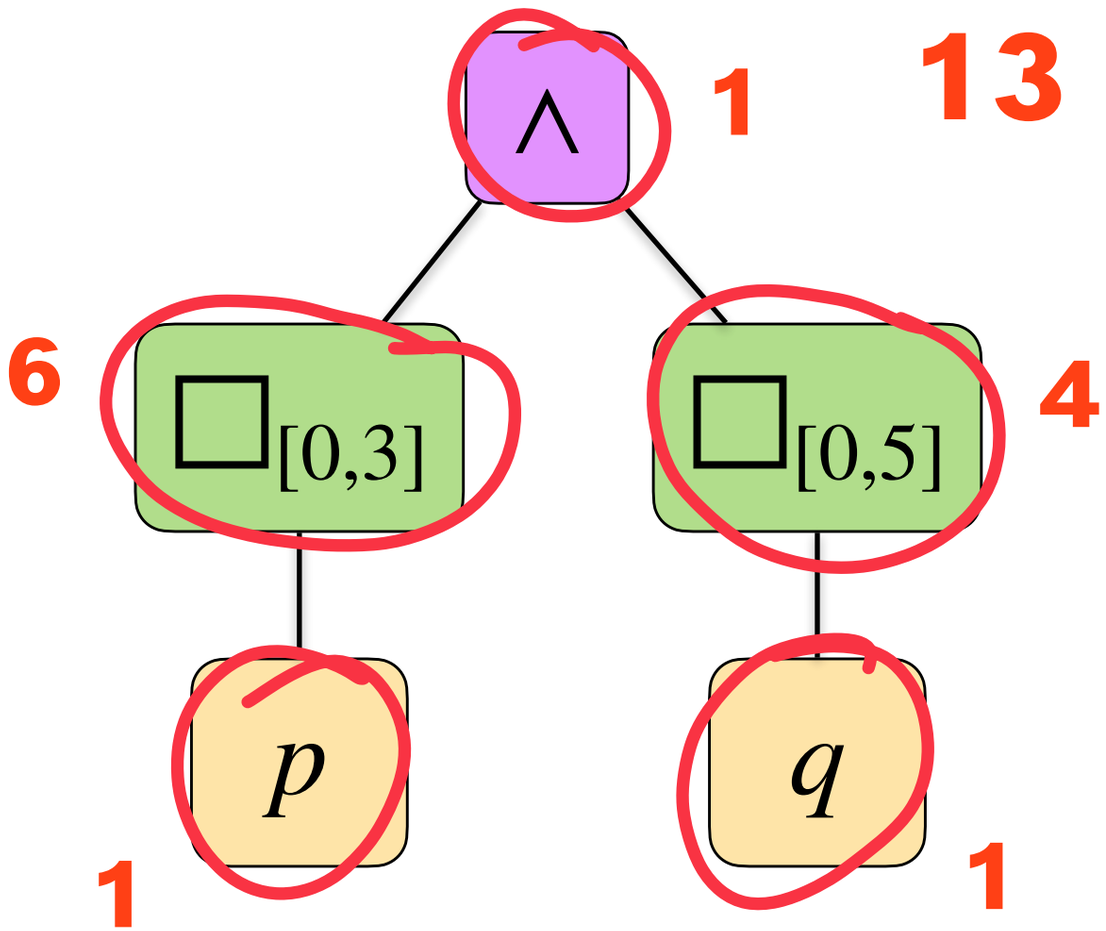

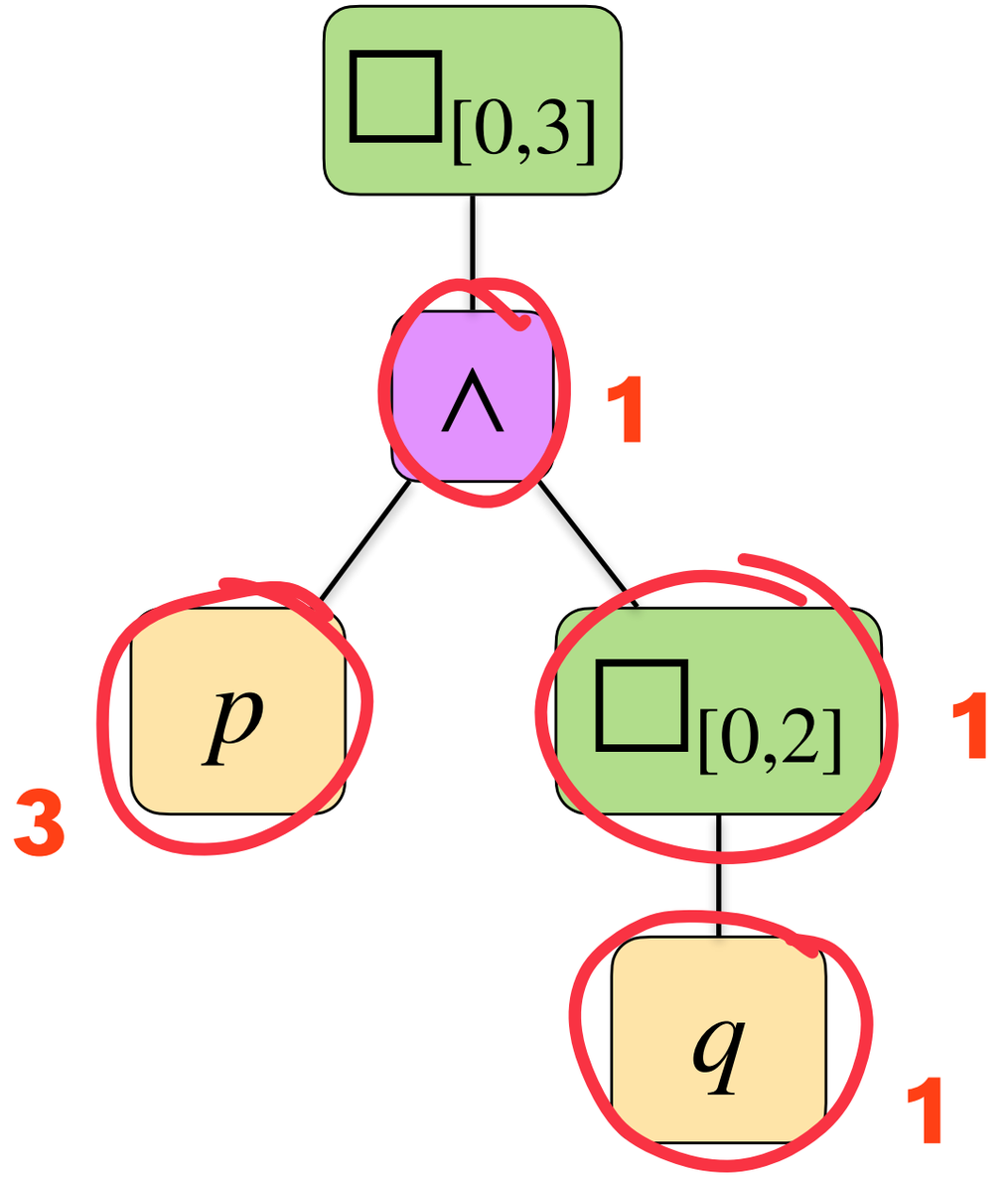

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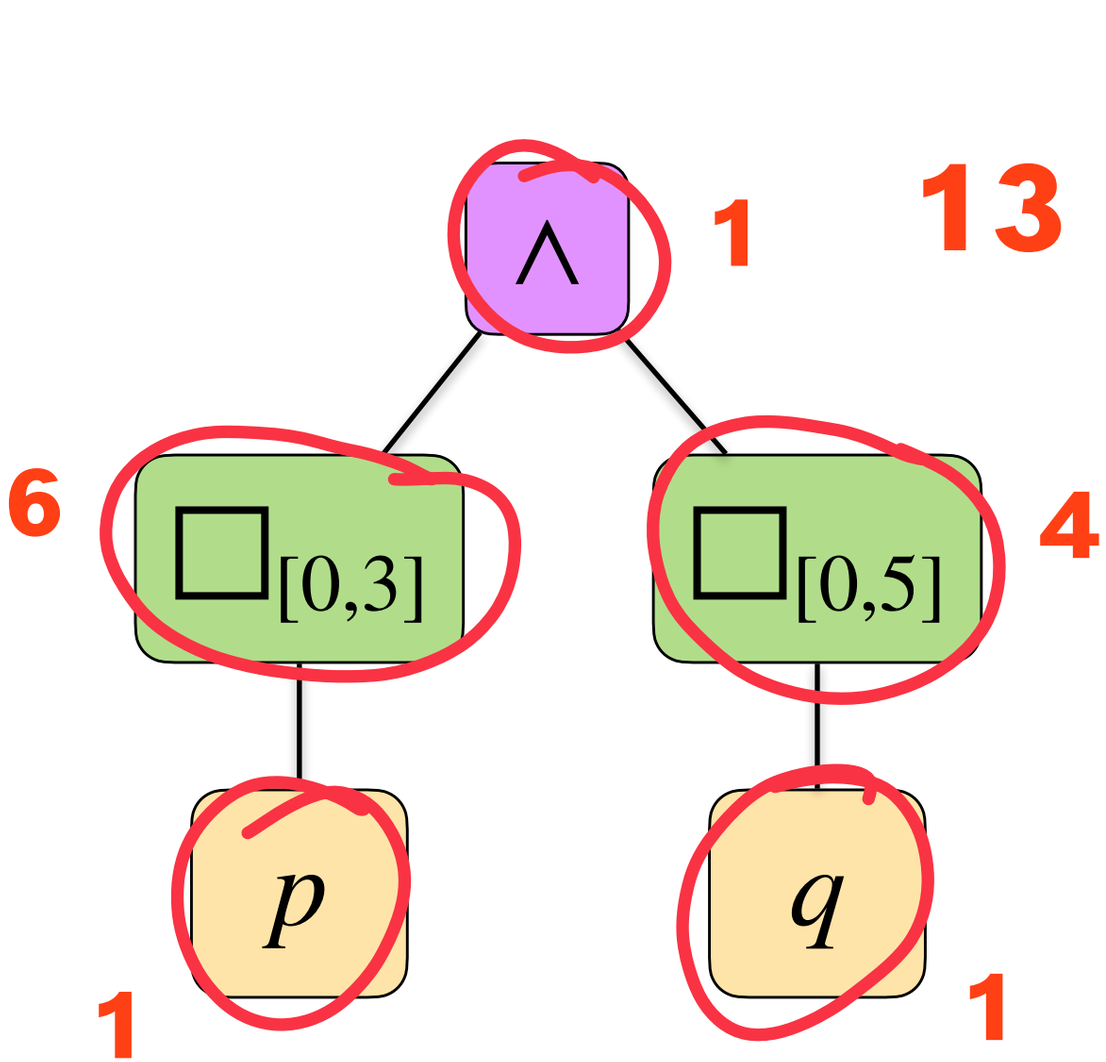

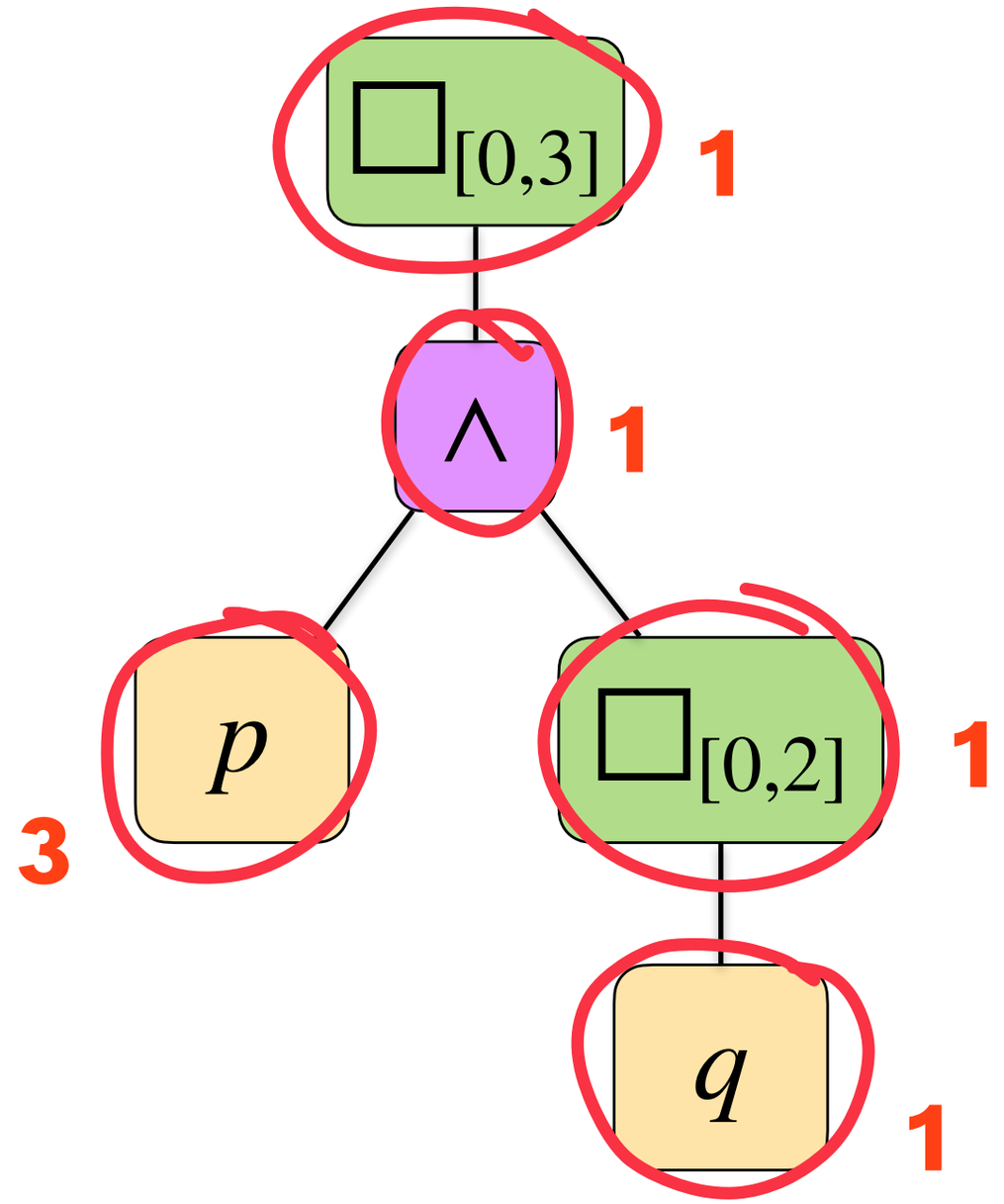

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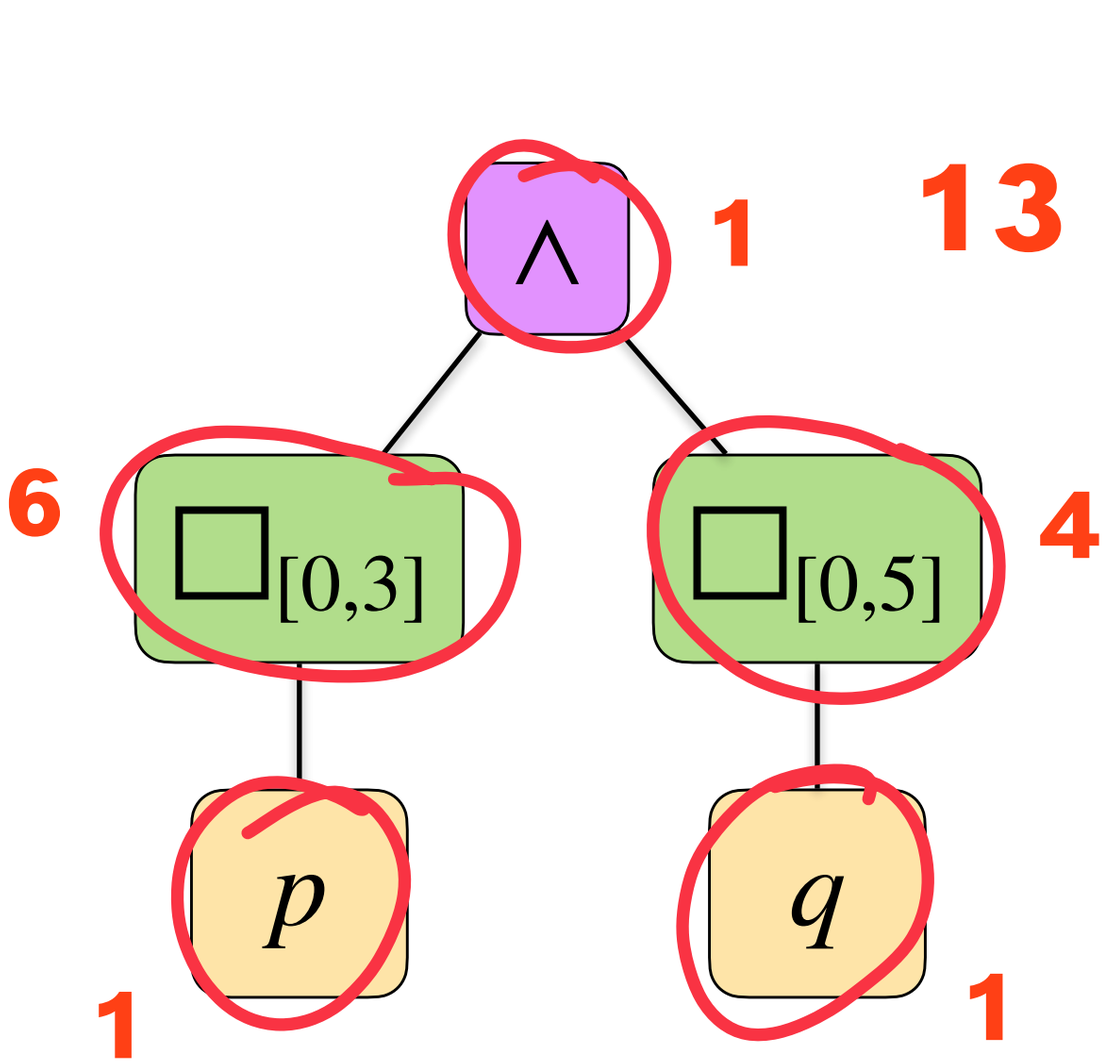

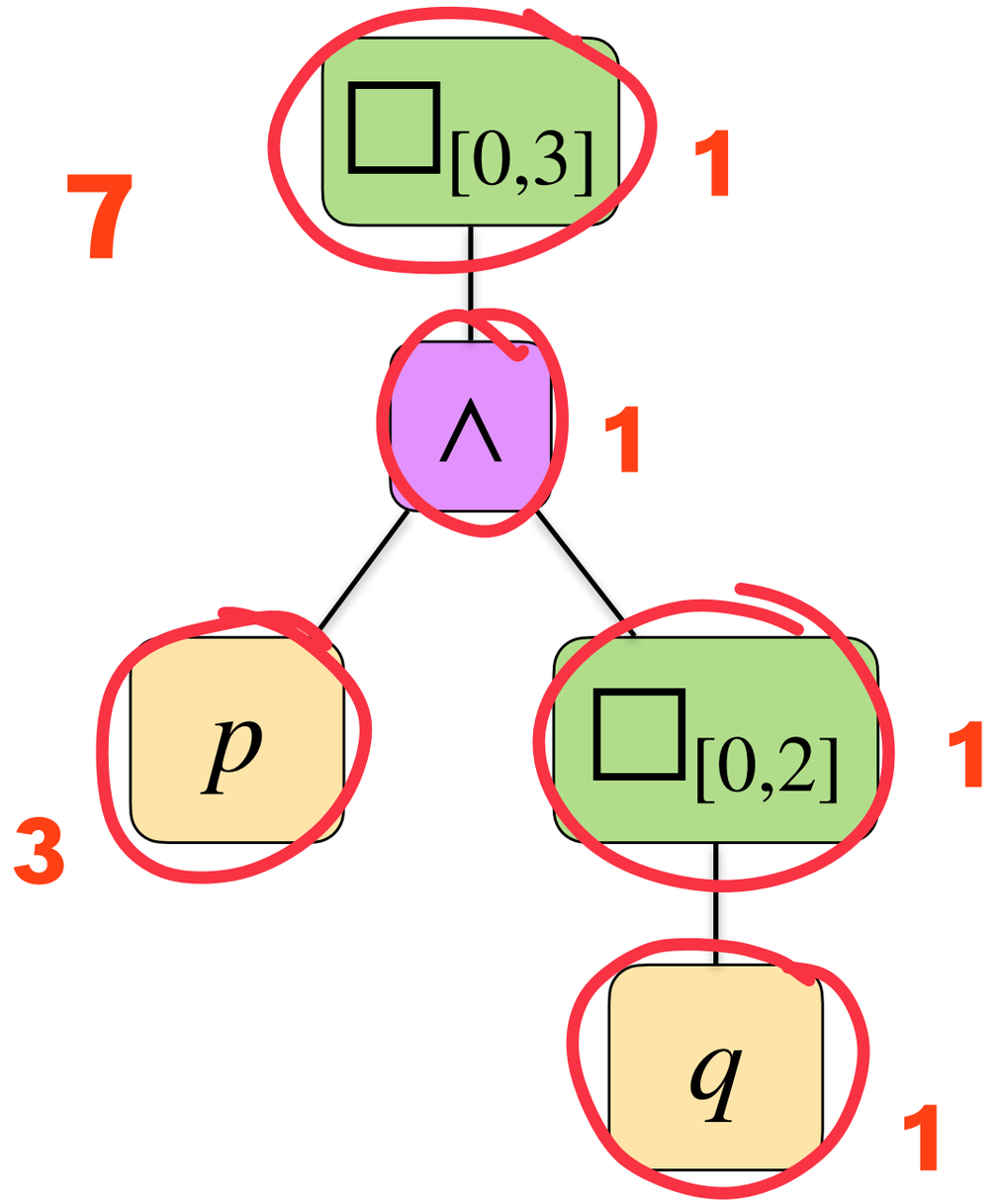

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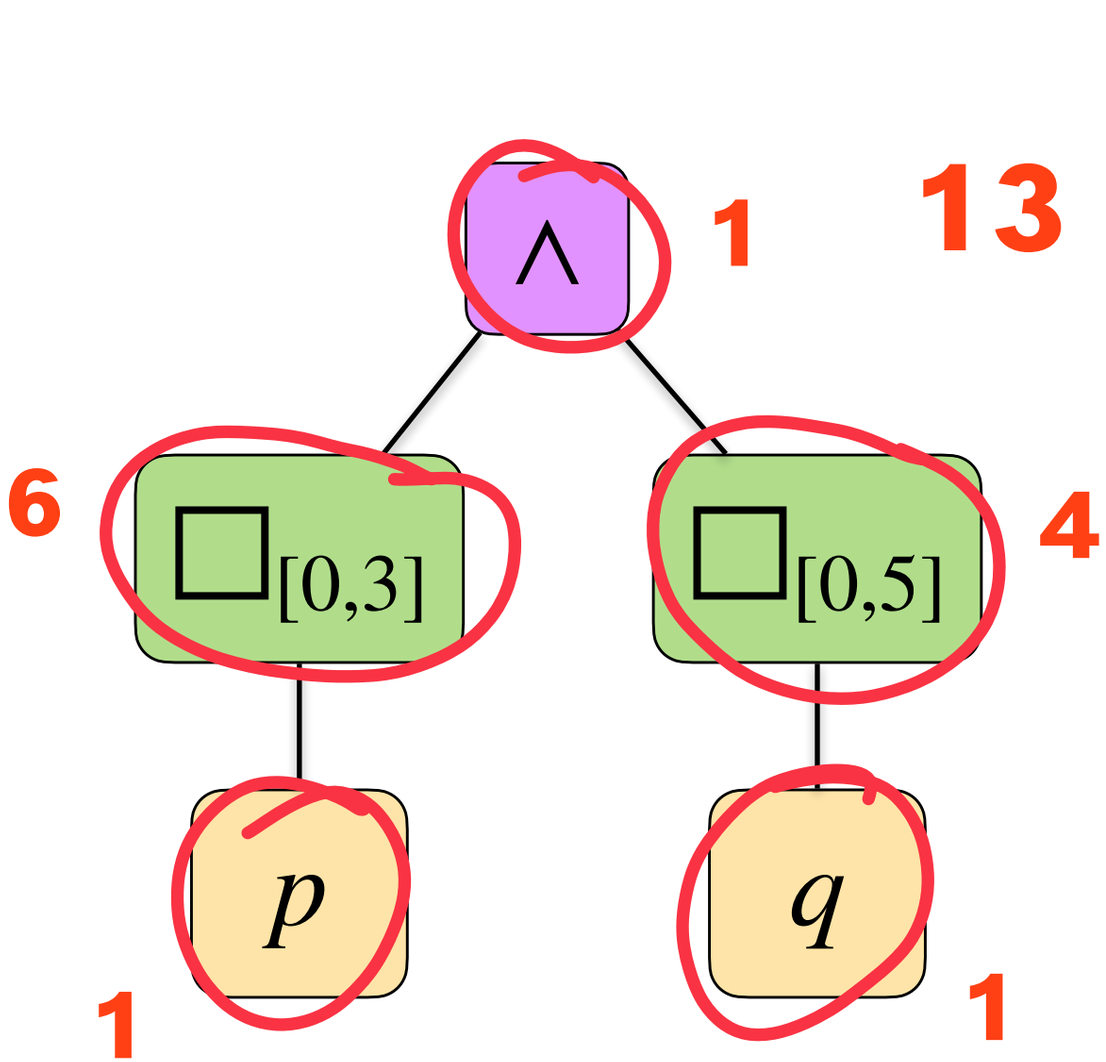
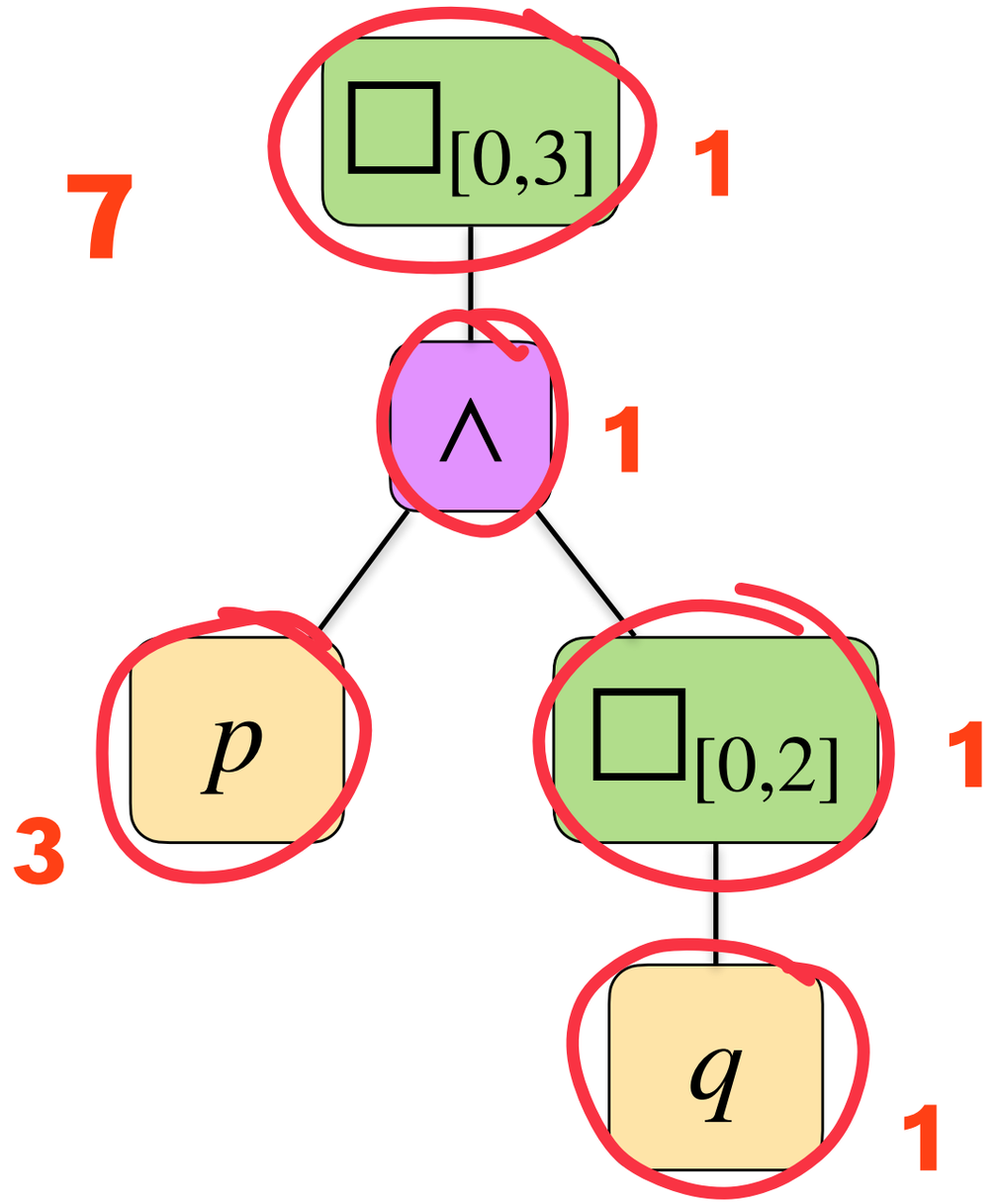


13 > 7



MLTL Rewrite Rules [19]

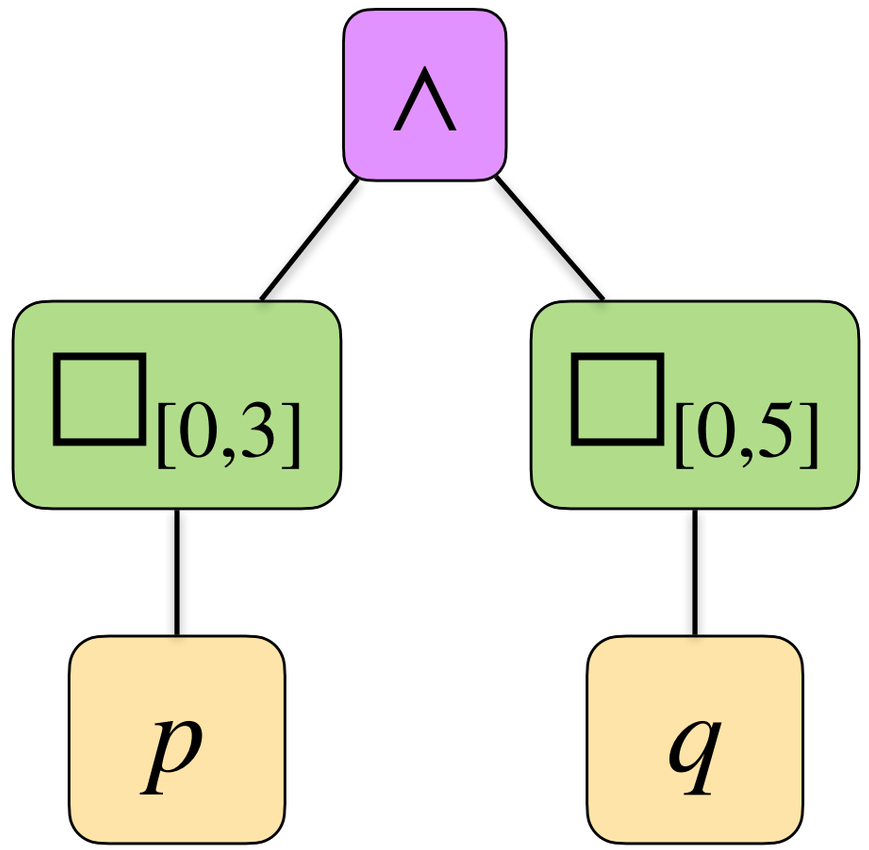
$\Box_{[l_1,u_1]}\Box_{[l_2,u_2]}\varphi \mapsto \Box_{[l_1+l_2,u_1+u_2]}\varphi$	$\Diamond_{[l_1,u_1]}\Diamond_{[l_2,u_2]}\varphi \mapsto \Diamond_{[l_1+l_2,u_1+u_2]}\varphi$	(R1)
$\Box_{[l_1,u_1]}\varphi \wedge \Box_{[l_2,u_2]}\psi \mapsto \Box_{[l_3,u_3]}(\Box_{[l_1-l_3,u_1-u_3]}\varphi \wedge \Box_{[l_2-l_3,u_2-u_3]}\psi)$		
$\Diamond_{[l_1,u_1]}\varphi \vee \Diamond_{[l_2,u_2]}\psi \mapsto \Diamond_{[l_3,u_3]}(\Diamond_{[l_1-l_3,u_1-u_3]}\varphi \vee \Diamond_{[l_2-l_3,u_2-u_3]}\psi)$		(R2)
where $l_3 = min(l_1, l_2), u_3 = l_3 + min(u_1 - l_1, u_2 - l_2), l_3 < u_3$		
$\Box_{[a,a]}\Diamond_{[l,u]}\varphi \mapsto \Diamond_{[l+a,u+a]}\varphi$	$\Diamond_{[l,u]}\Box_{[a,a]}\varphi \mapsto \Diamond_{[l+a,u+a]}\varphi$	(R3)
$\Diamond_{[a,a]}\Box_{[l,u]}\varphi \mapsto \Box_{[l+a,u+a]}\varphi$	$\Box_{[l,u]}\Diamond_{[a,a]}\varphi \mapsto \Box_{[l+a,u+a]}\varphi$	
$\Box_{[l_1,u_1]}\varphi \wedge \Box_{[l_2,u_2]}\varphi \mapsto \Box_{[l_1,u_3]}\varphi$	$\Diamond_{[l_1,u_1]}\varphi \vee \Diamond_{[l_2,u_2]}\varphi \mapsto \Diamond_{[l_1,u_2]}\varphi$	(R4)
where $l_1 \leq l_2 \leq u_1 + 1, u_3 = max(u_1, u_2)$		
$\Box_{[l_1,u_1]}\varphi \vee \Box_{[l_2,u_2]}\varphi \mapsto \Box_{[l_2,u_2]}\varphi$	$\Diamond_{[l_1,u_1]}\varphi \wedge \Diamond_{[l_2,u_2]}\varphi \mapsto \Diamond_{[l_2,u_2]}\varphi$	(R5)
where $l_1 \leq l_2 \leq u_2 \leq u_1$		
$\Box_{[a,a]}(\varphi\ \mathcal{U}_{[l,u]}\ \psi) \mapsto \varphi\ \mathcal{U}_{[l+a,u+a]}\ \psi$	$(\Box_{[a,a]}\varphi)\ \mathcal{U}_{[l,u]}\ (\Box_{[a,a]}\psi) \mapsto \varphi\ \mathcal{U}_{[l+a,u+a]}\ \psi$	(R6)
$(\varphi_1\ \mathcal{U}_{[l,u_1]}\ \varphi_2) \wedge (\varphi_3\ \mathcal{U}_{[l,u_2]}\ \varphi_2) \mapsto (\varphi_1 \wedge \varphi_3)\ \mathcal{U}_{[l,u_1]}\ \varphi_2$		(R7)
where $l \leq u_1, l \leq u_2, u_1 \leq u_2$		
$\varphi\ \mathcal{U}_{[l_1,u_1]}\ \Box_{[0,u_2]}\varphi \mapsto \Box_{[l_1,l_1+u_2]}\varphi$	$\varphi\ \mathcal{U}_{[l_1,u_1]}\ \Diamond_{[0,u_2]}\varphi \mapsto \Diamond_{[l_1,l_1+u_2]}\varphi$	(R8)

How to apply rewrite rules algorithmically?

- **Order of rewrites matter** — applying one rule may **disable** the application of another.
  - Assume R_1 disables R_3
  - $R_1 \longrightarrow R_2$
  - $R_2 \longrightarrow R_3 \longrightarrow R_1$
  - ...
- Classic problem in **program optimization [20]**
- Solution: **Equality Saturation [21]**

MLTL Equality Saturation

$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$



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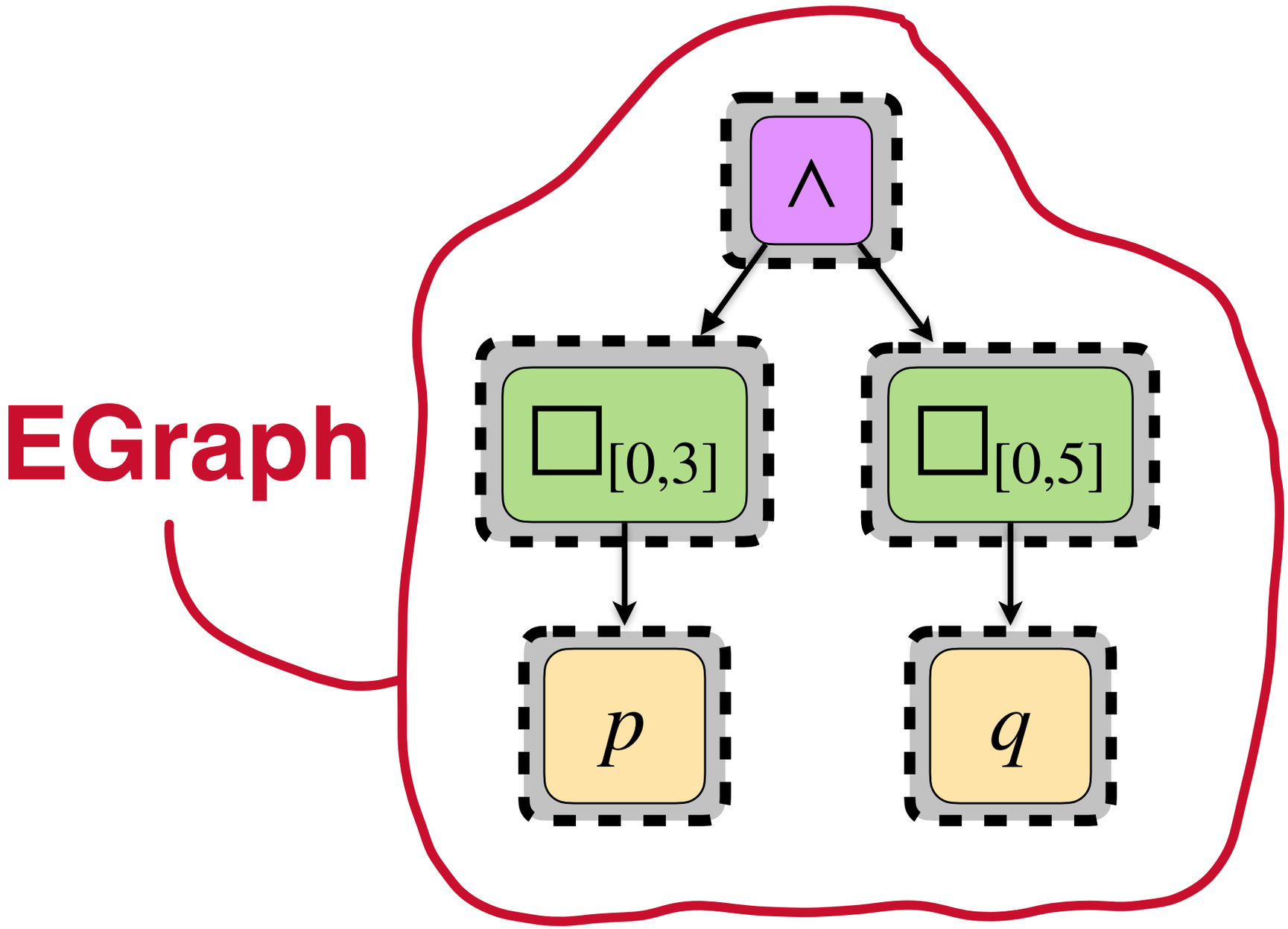

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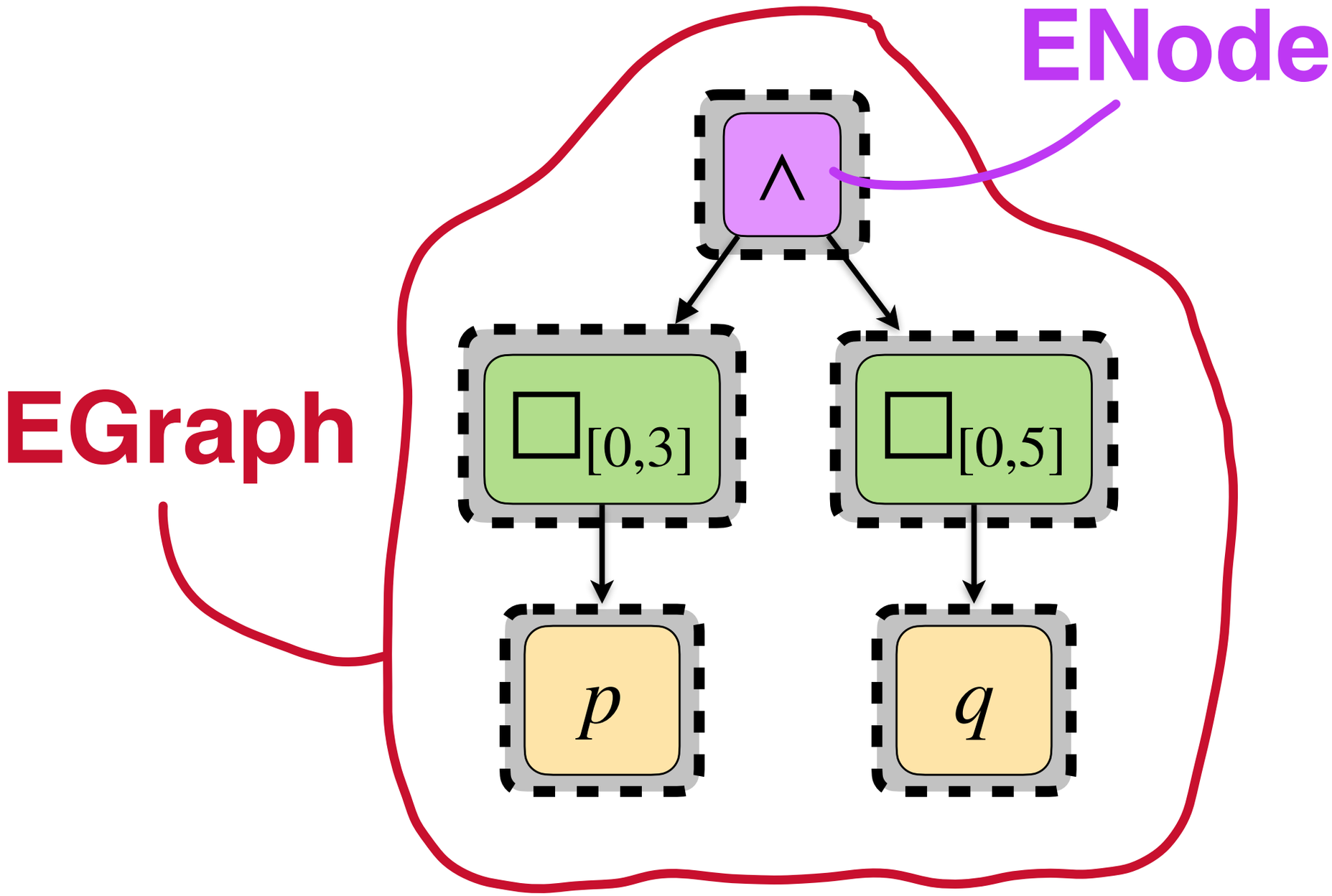

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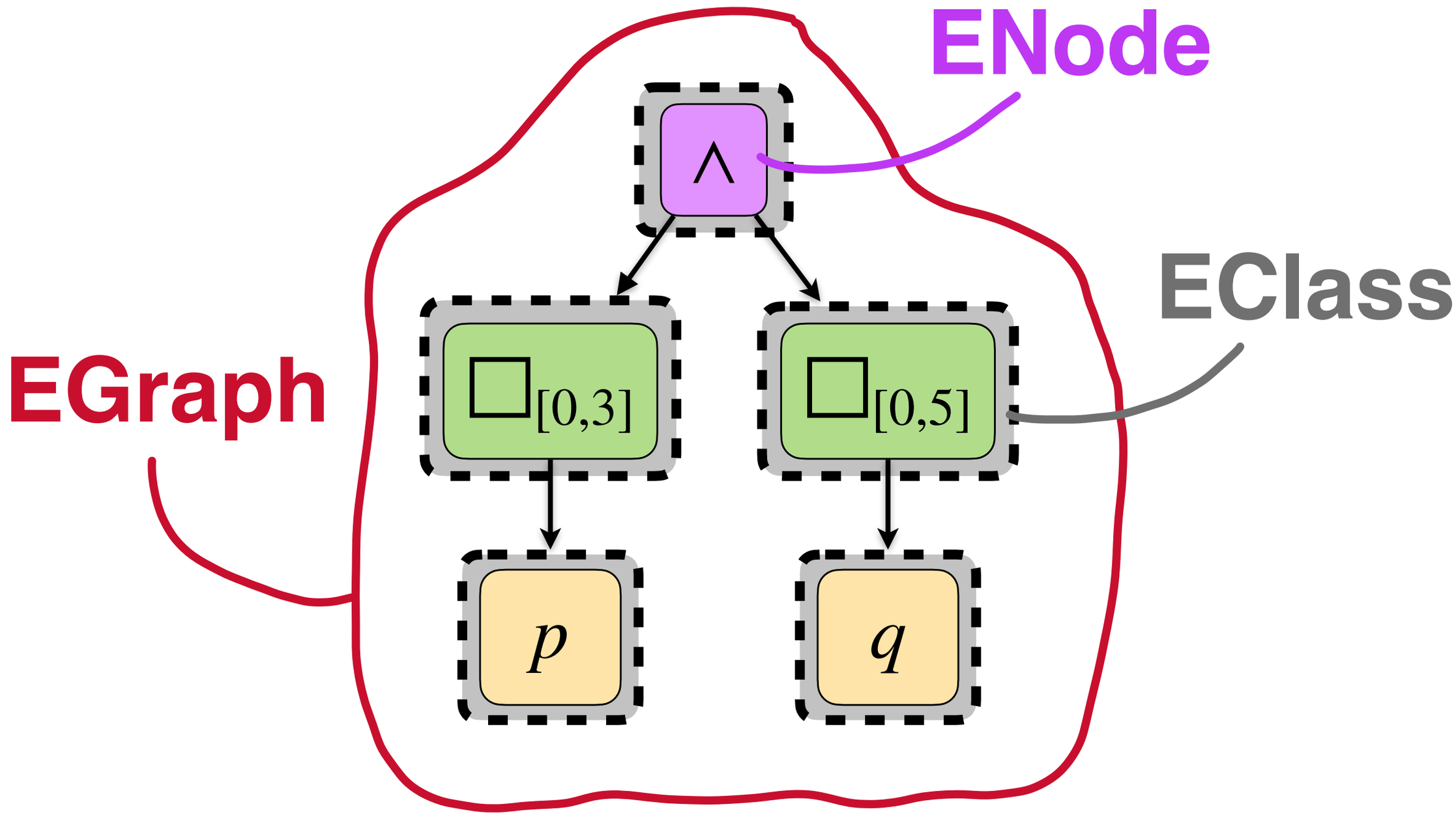

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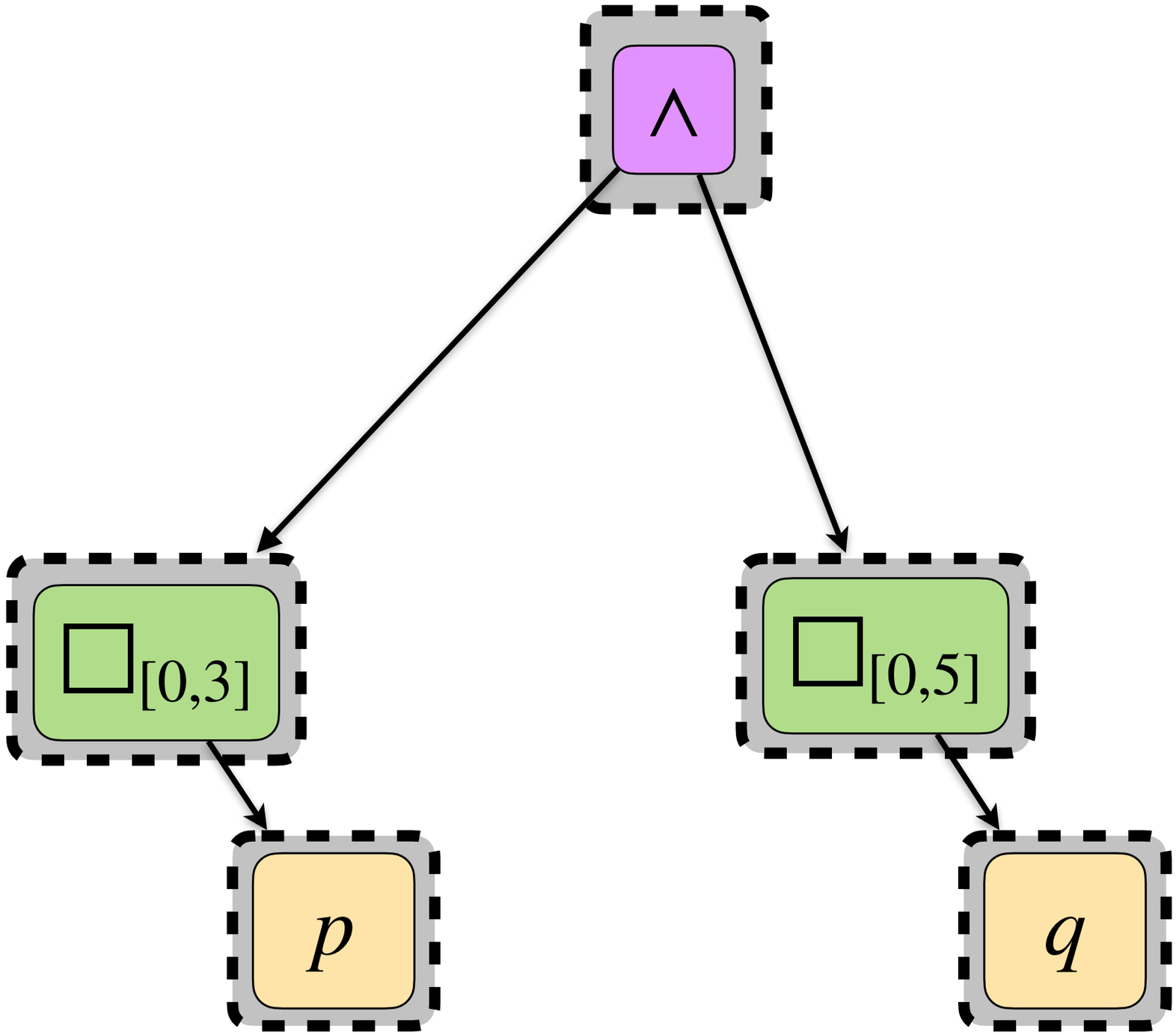

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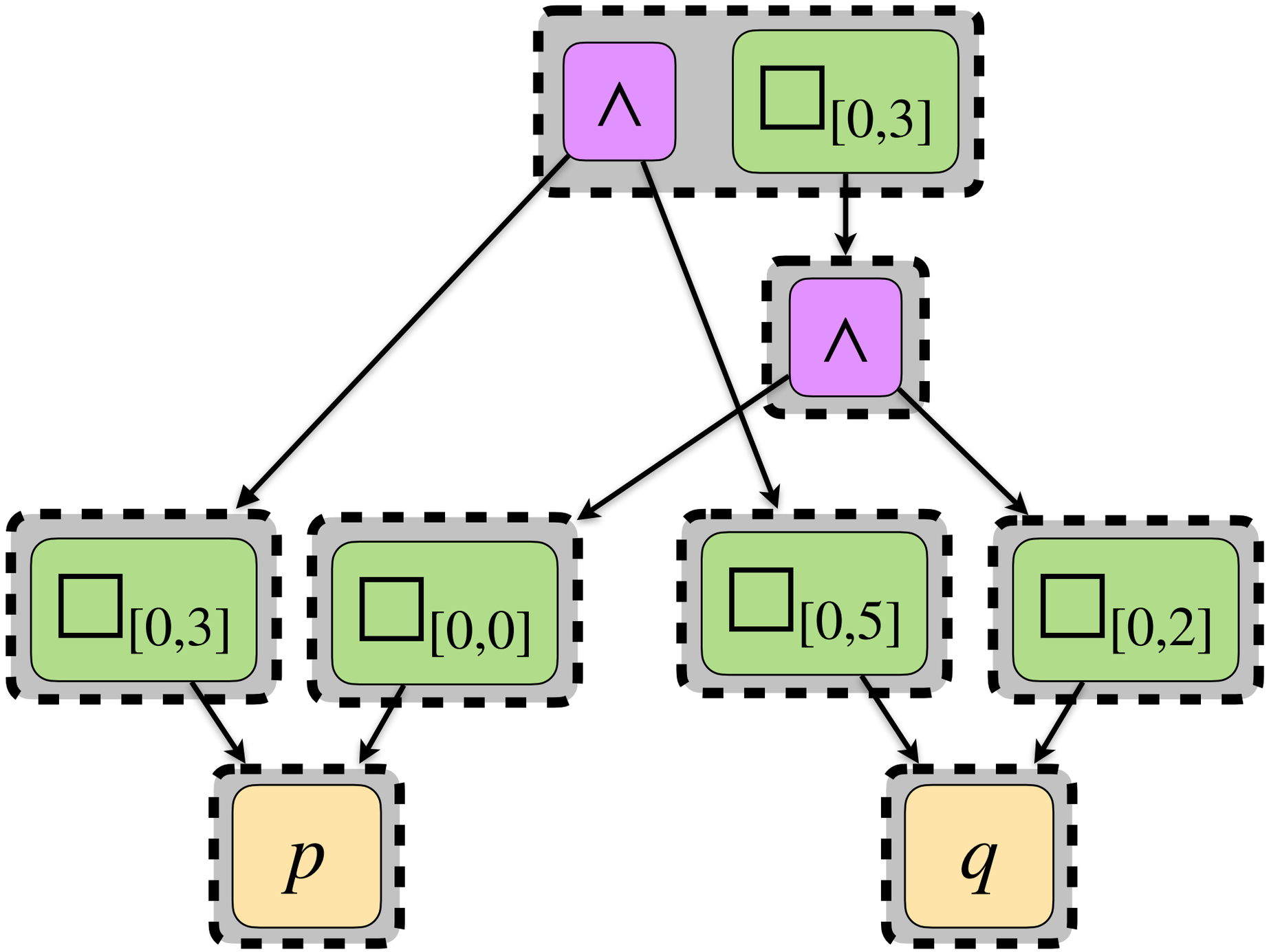

MLTL Equality Saturation

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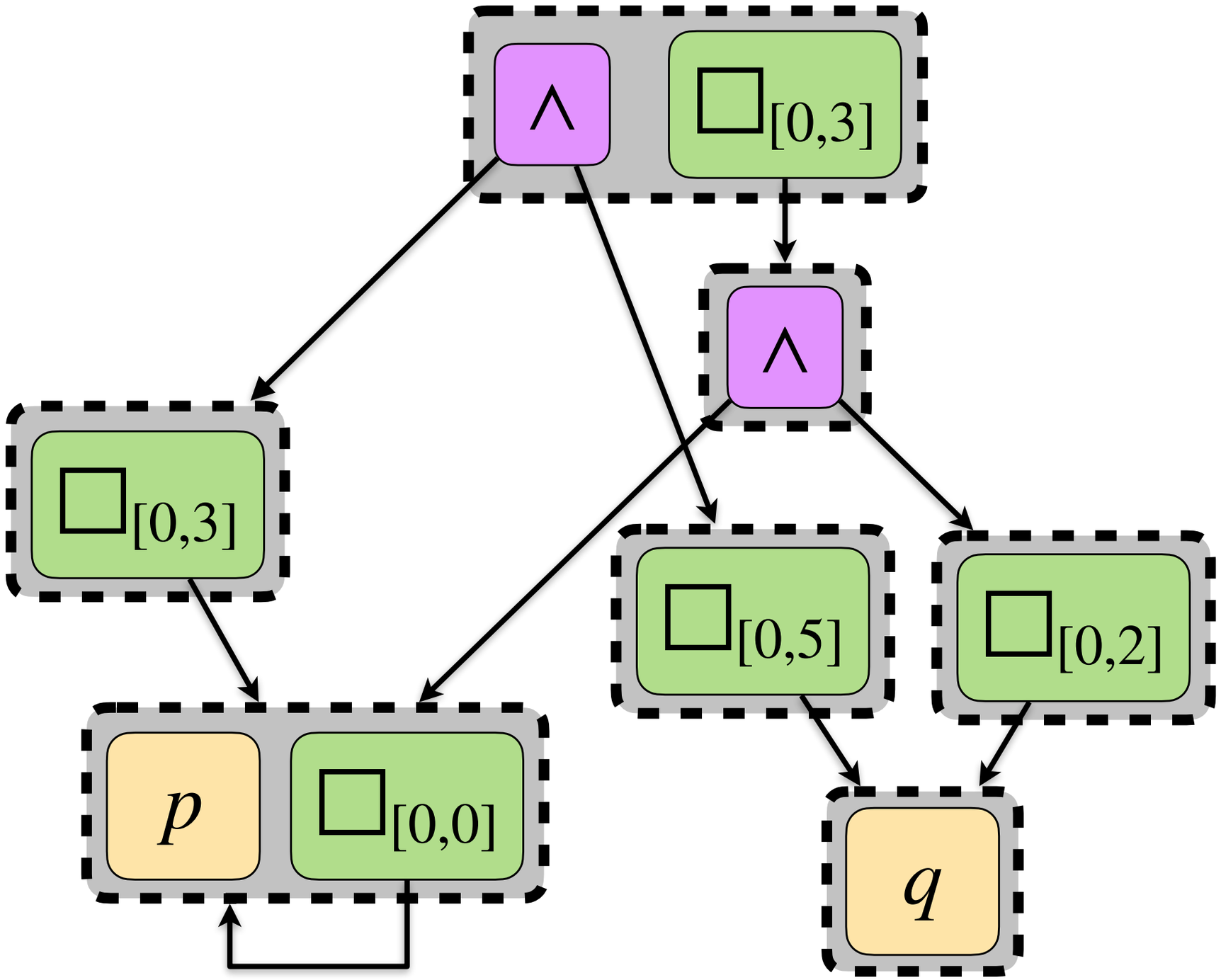

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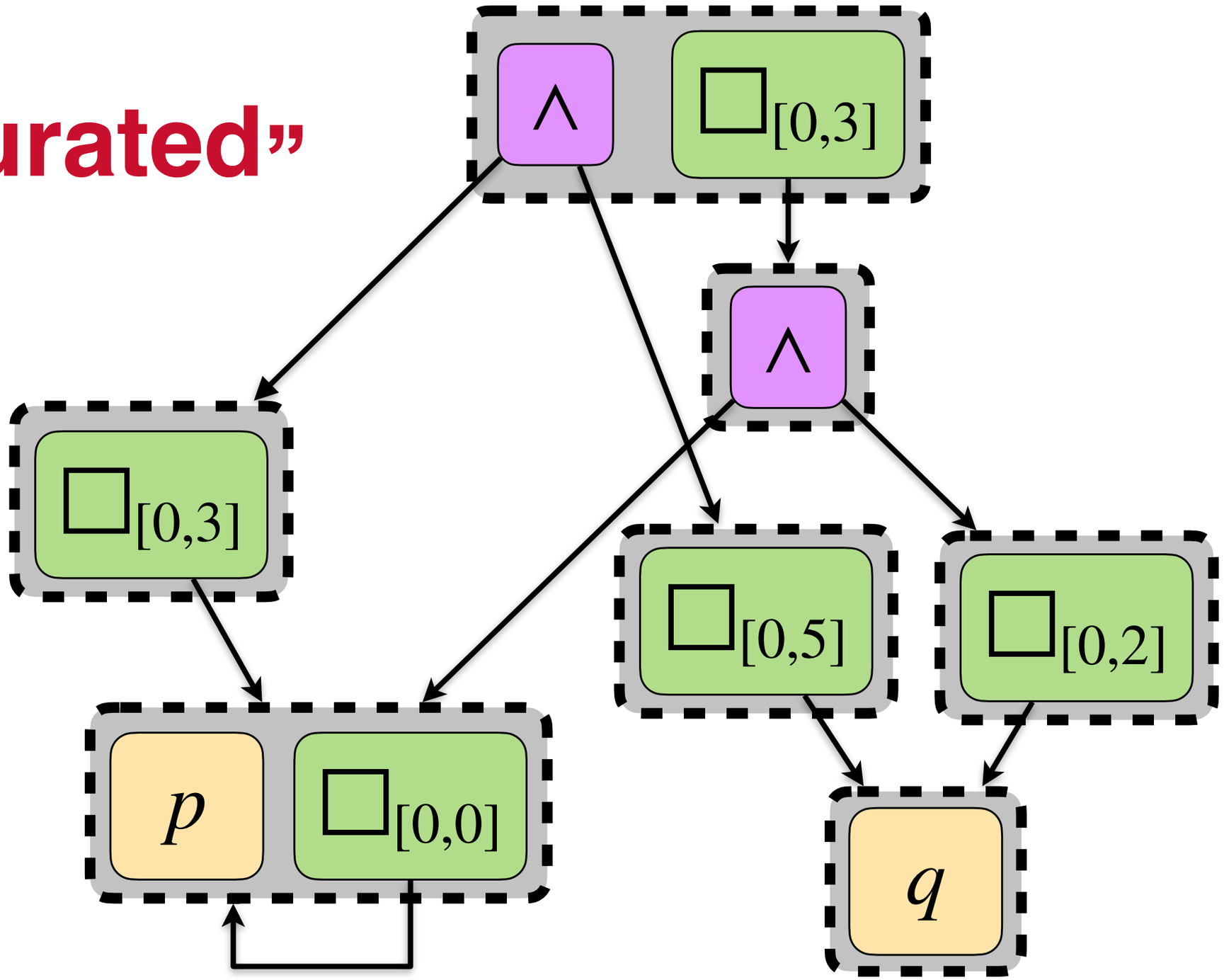
“Saturated”



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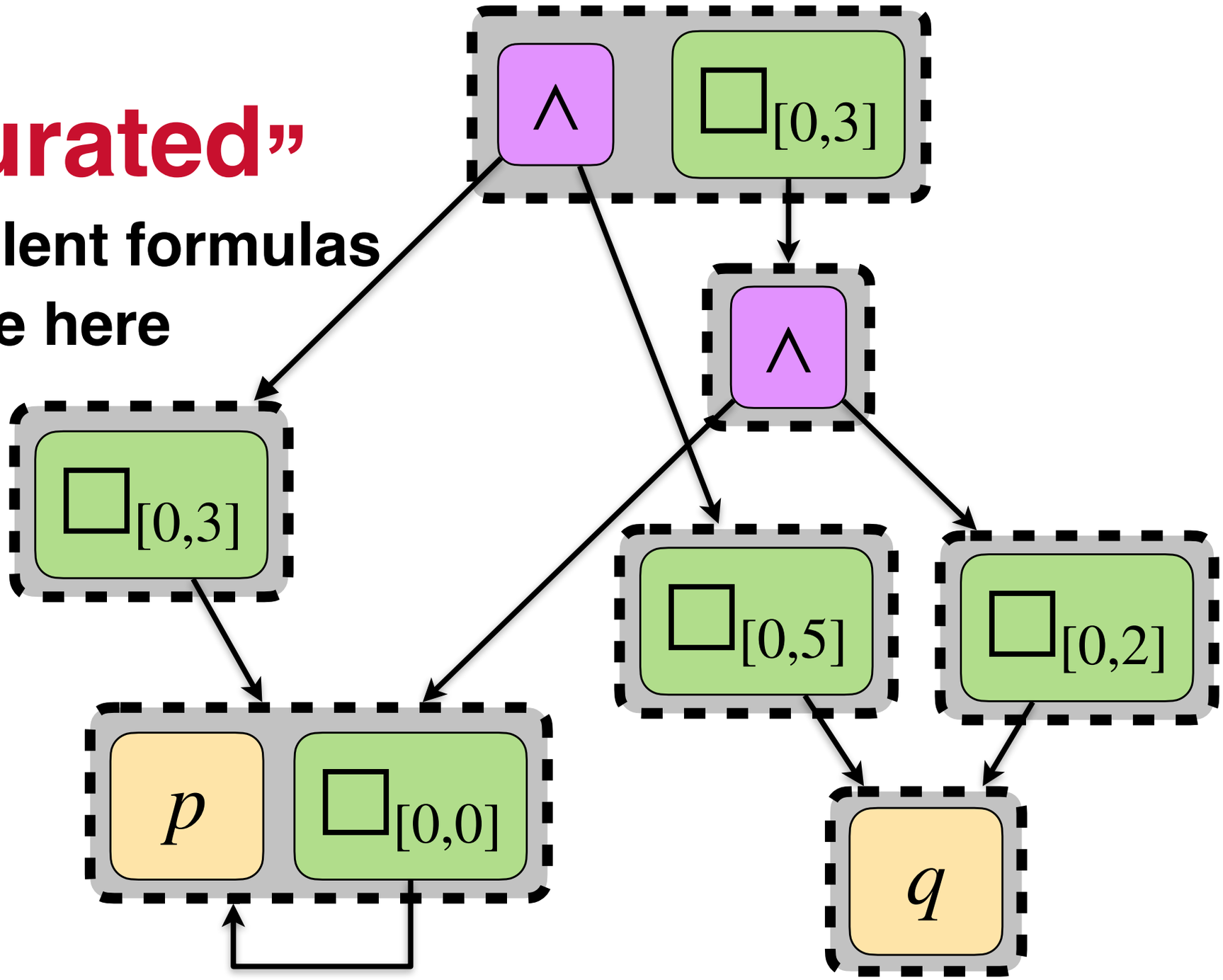
“Saturated”

All equivalent formulas to orig. are here



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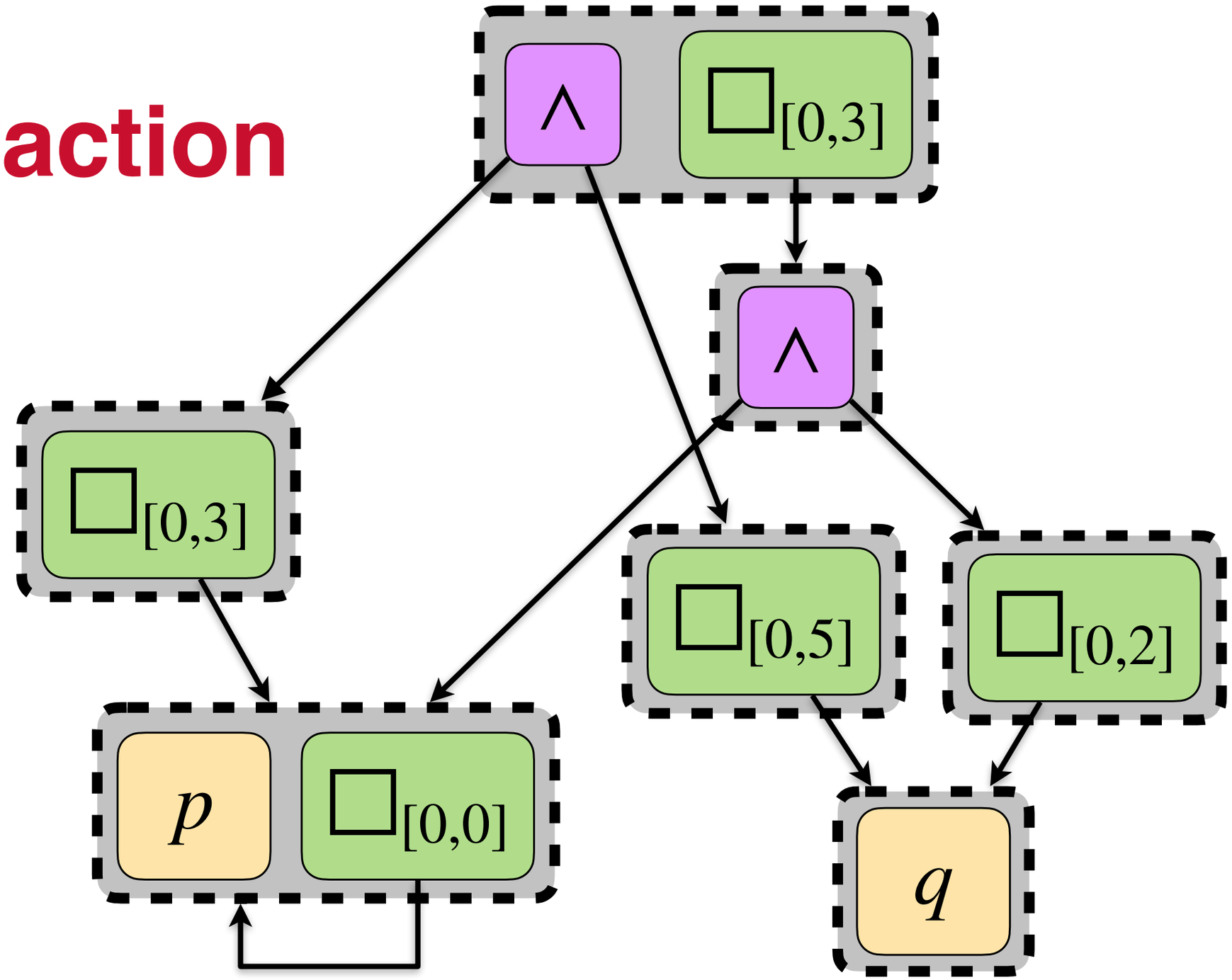
Extraction



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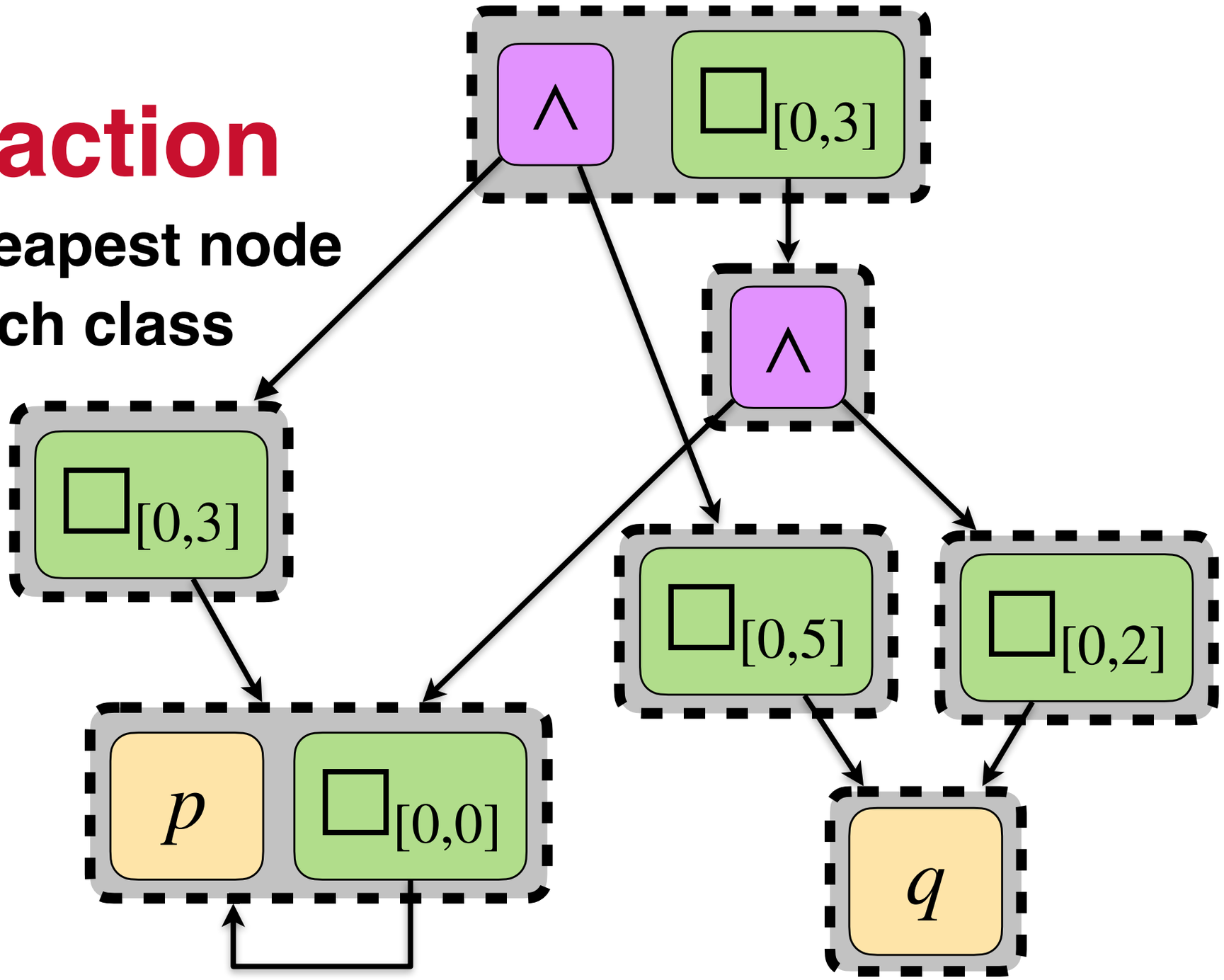
Extraction

Pick cheapest node from each class



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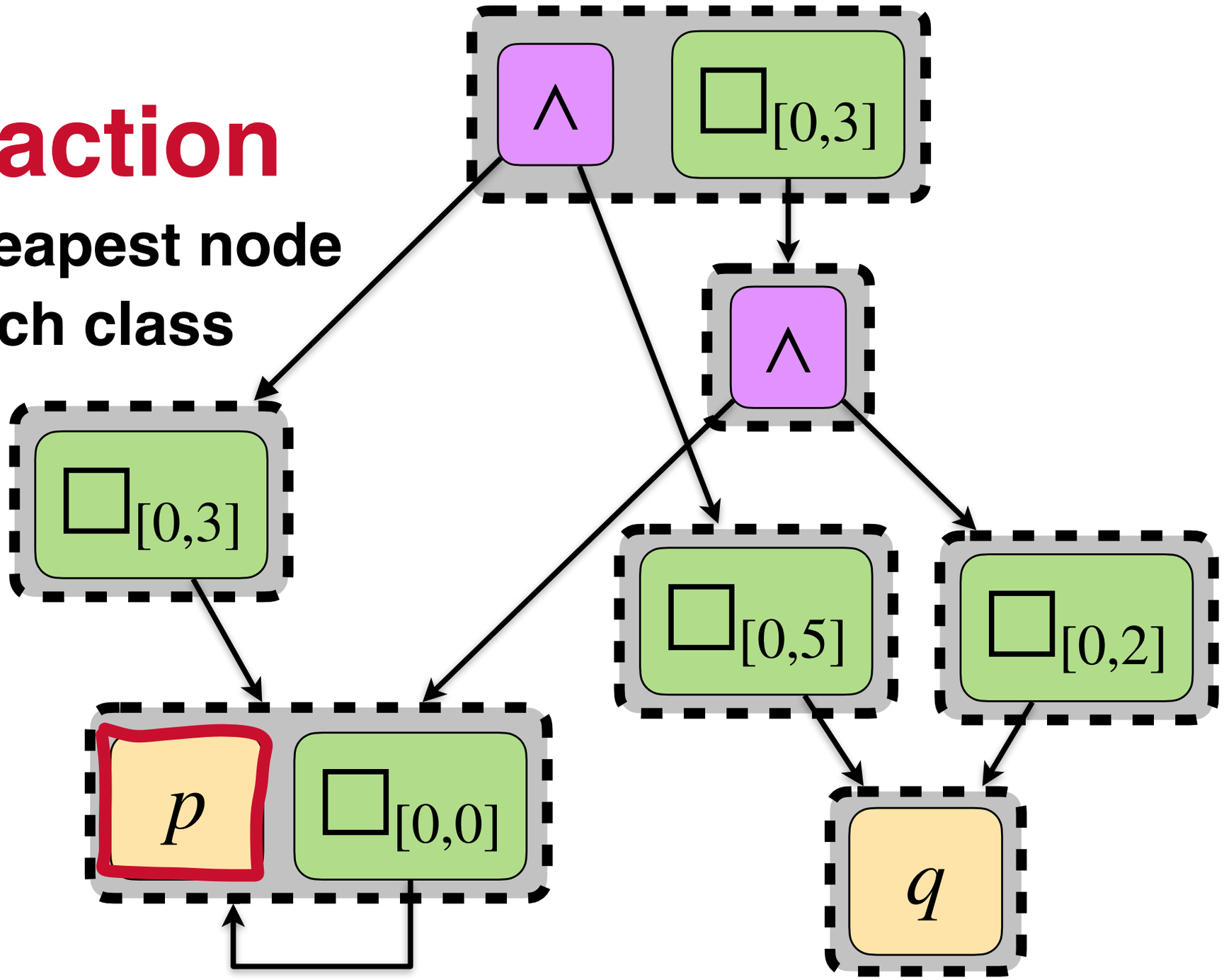

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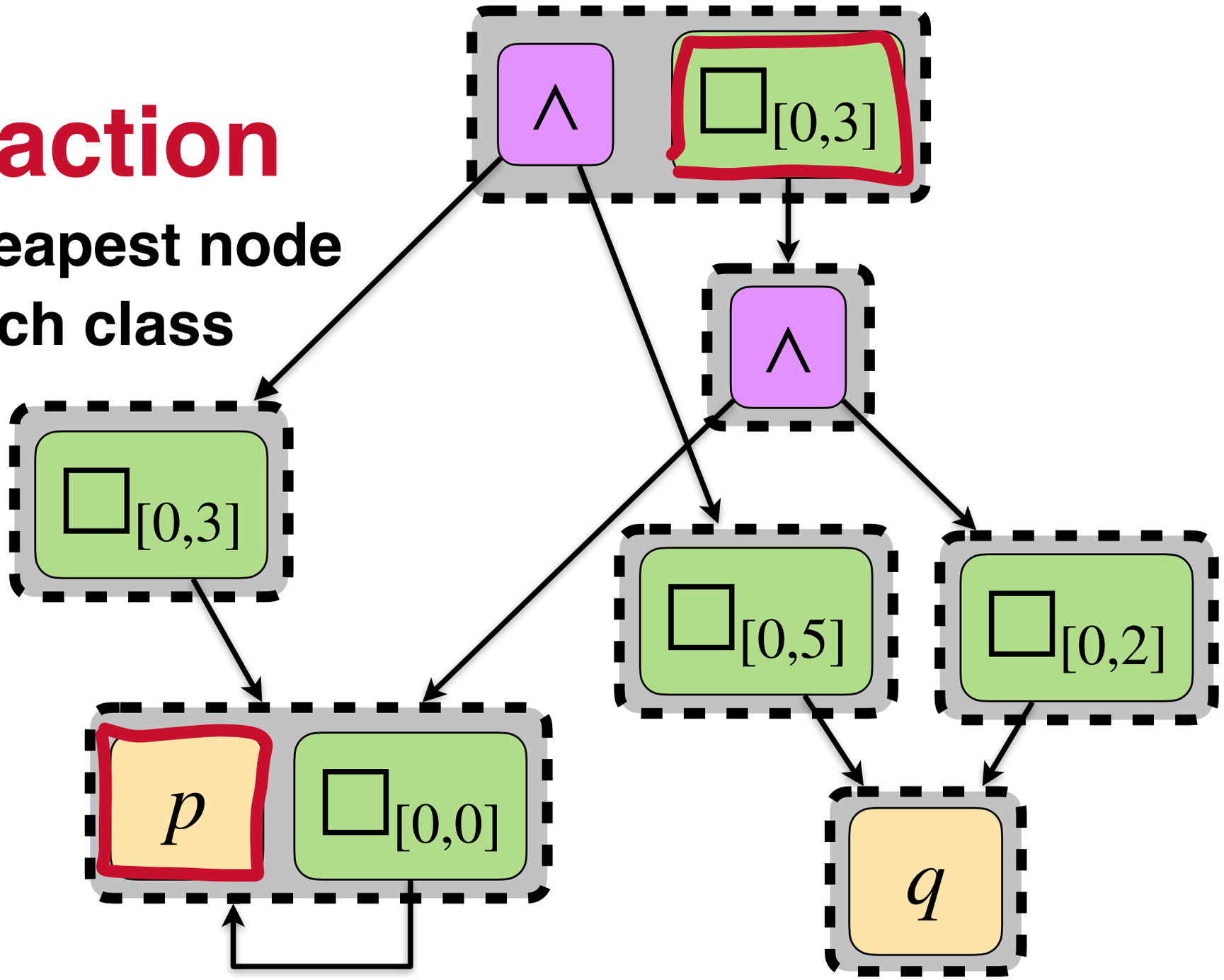

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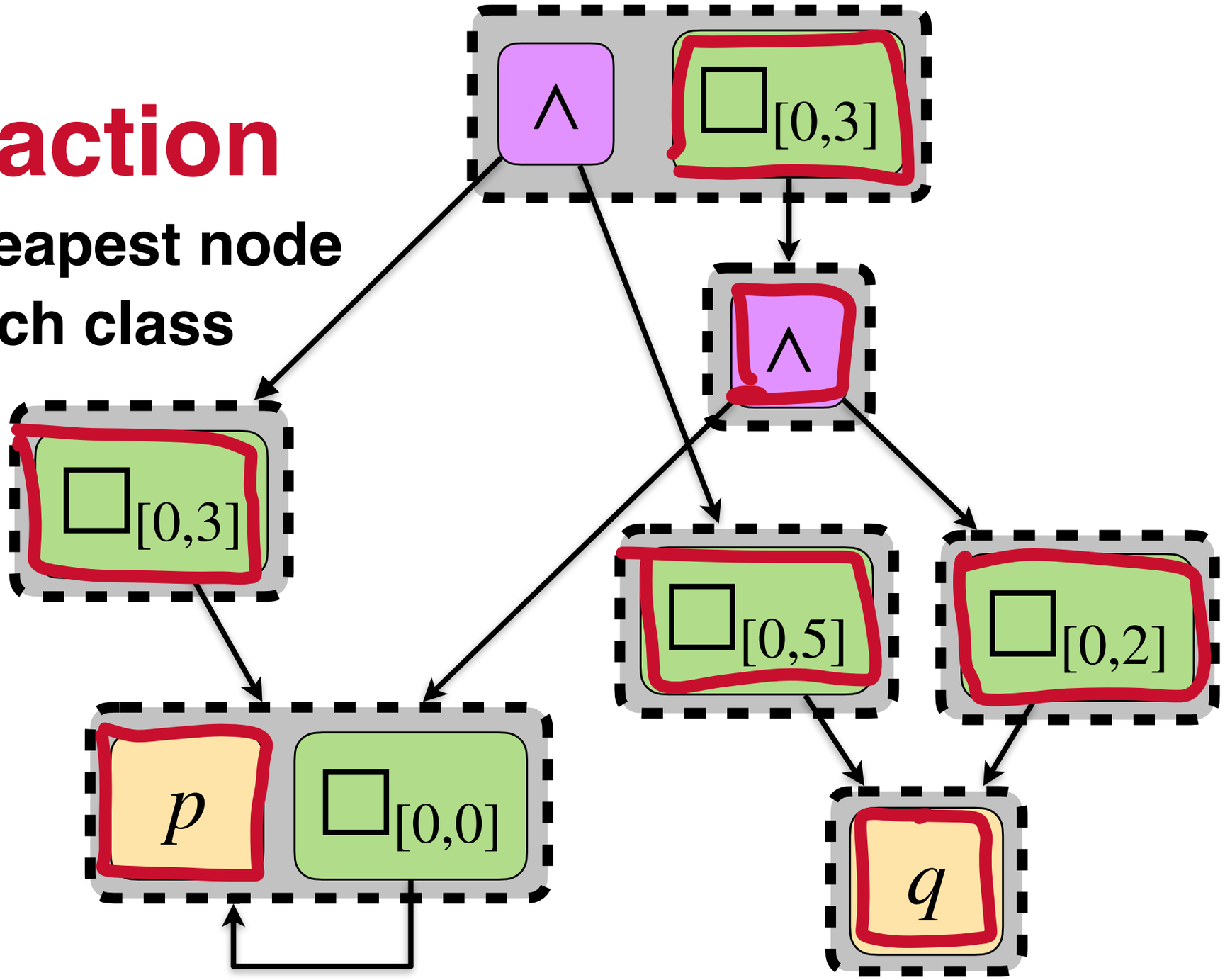
Extraction

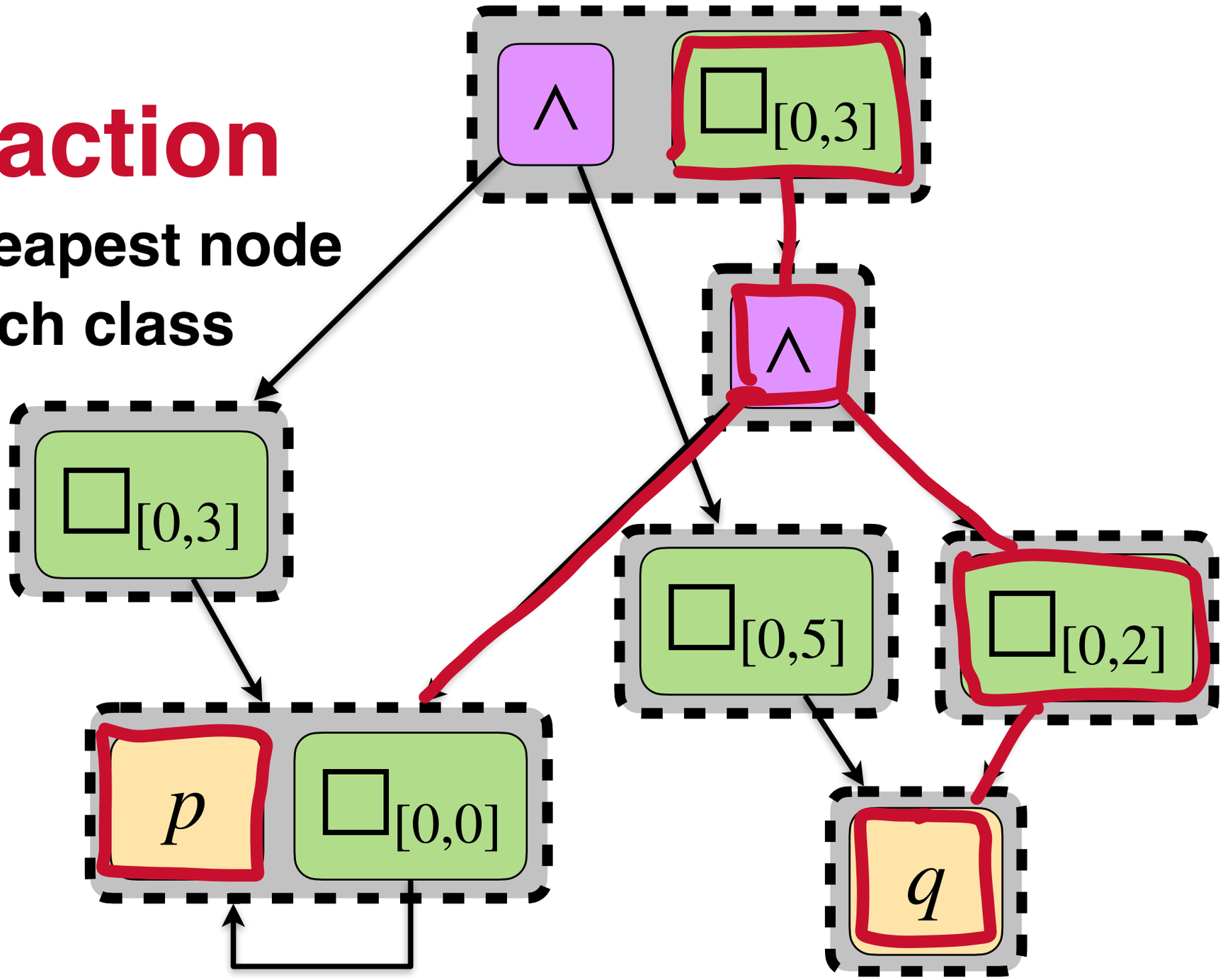
Pick cheapest node from each class



$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$
$$\Rightarrow \Box_{[0,3]} (\Box_{[0,0]} p \wedge \Box_{[0,2]} q)$$
$$\Rightarrow \Box_{[0,3]} (p \wedge \Box_{[0,2]} q)$$

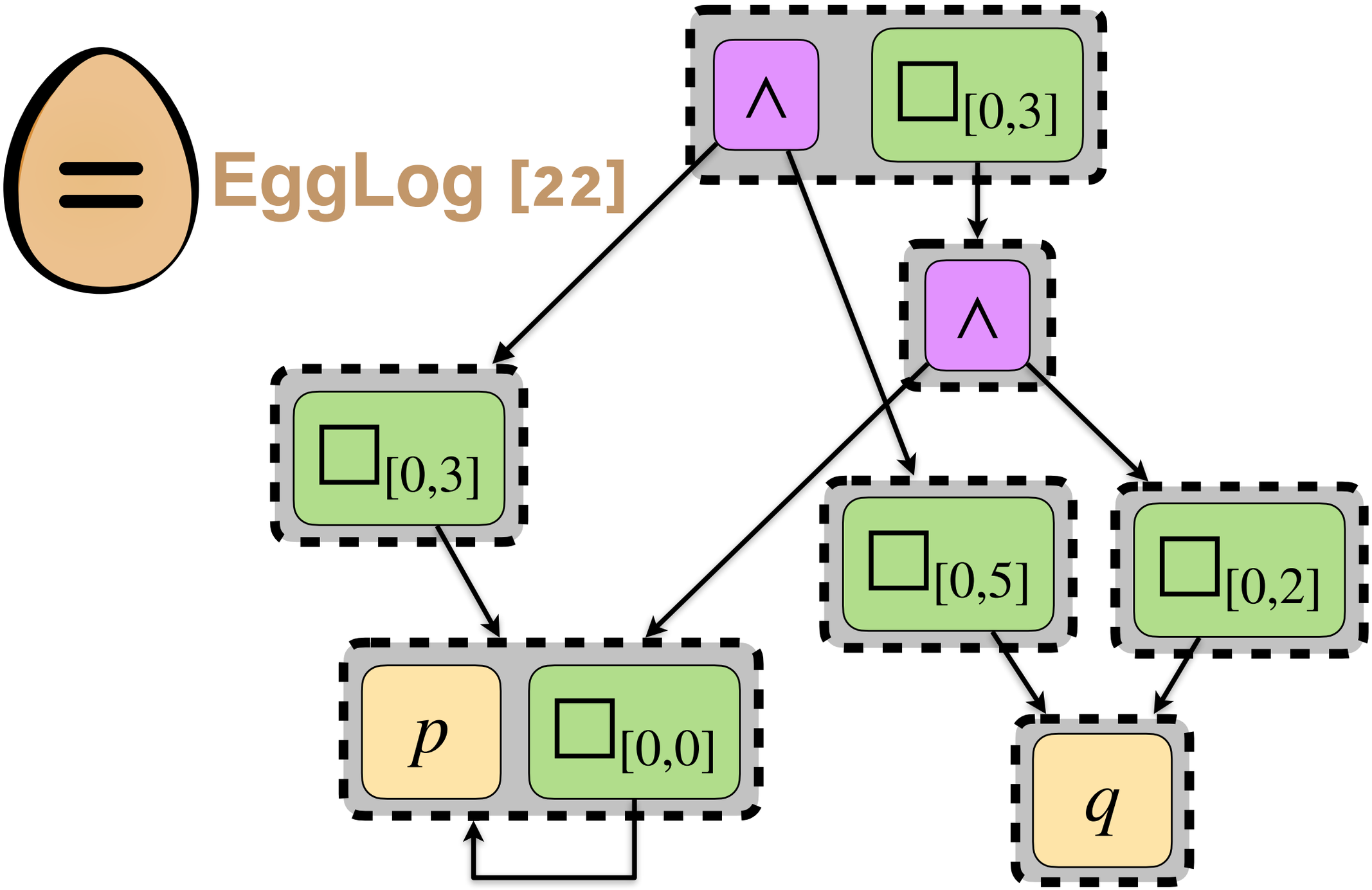
Extraction

Pick cheapest node from each class

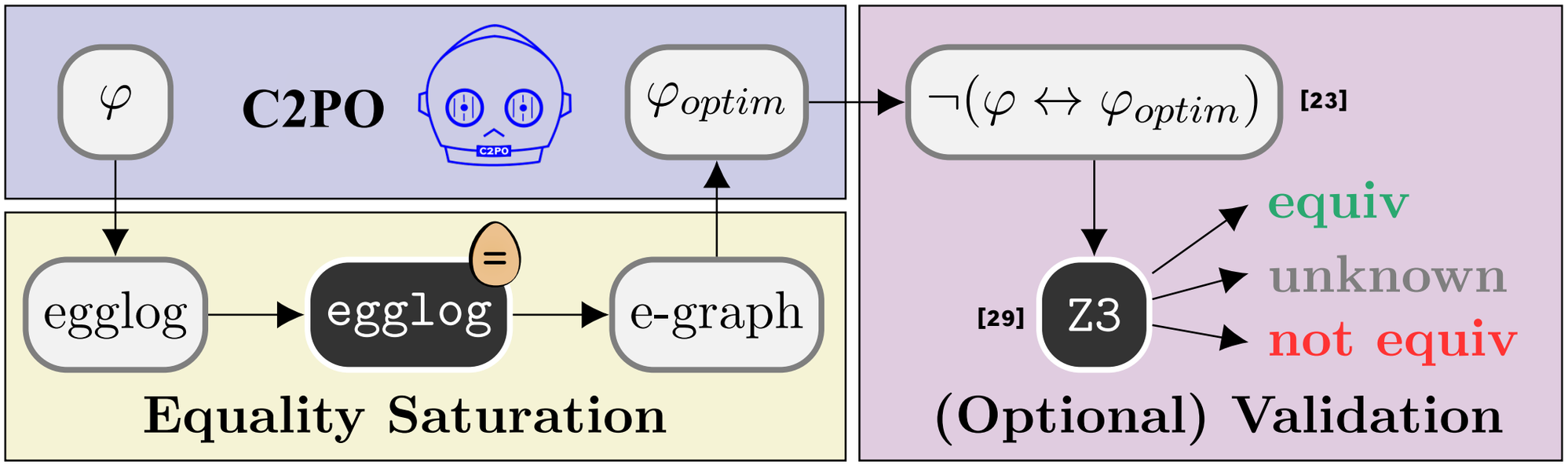


MLTL Equality Saturation

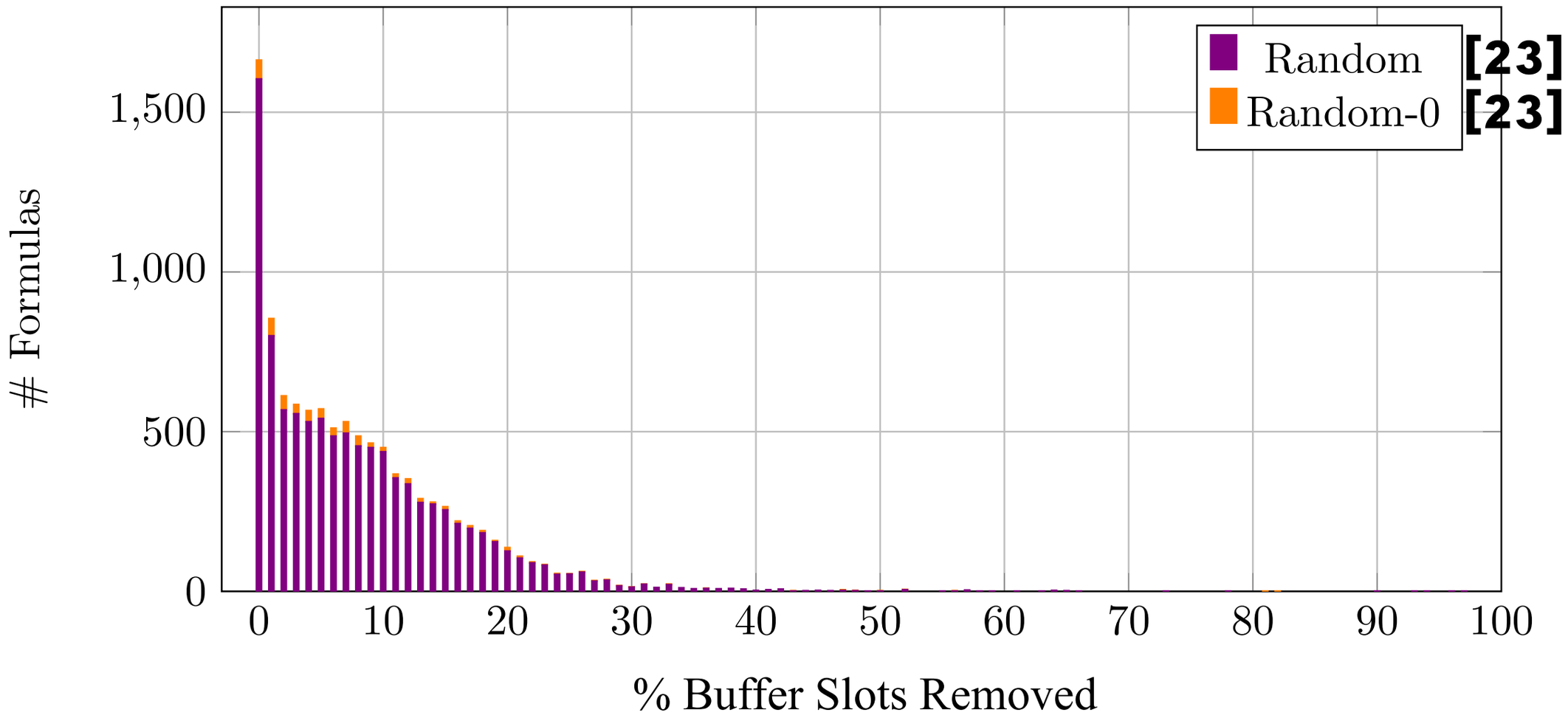
$$\Box_{[0,3]} p \wedge \Box_{[0,5]} q$$
$$\Rightarrow \Box_{[0,3]} (\Box_{[0,0]} p \wedge \Box_{[0,2]} q)$$
$$\Rightarrow \Box_{[0,3]} (p \wedge \Box_{[0,2]} q)$$



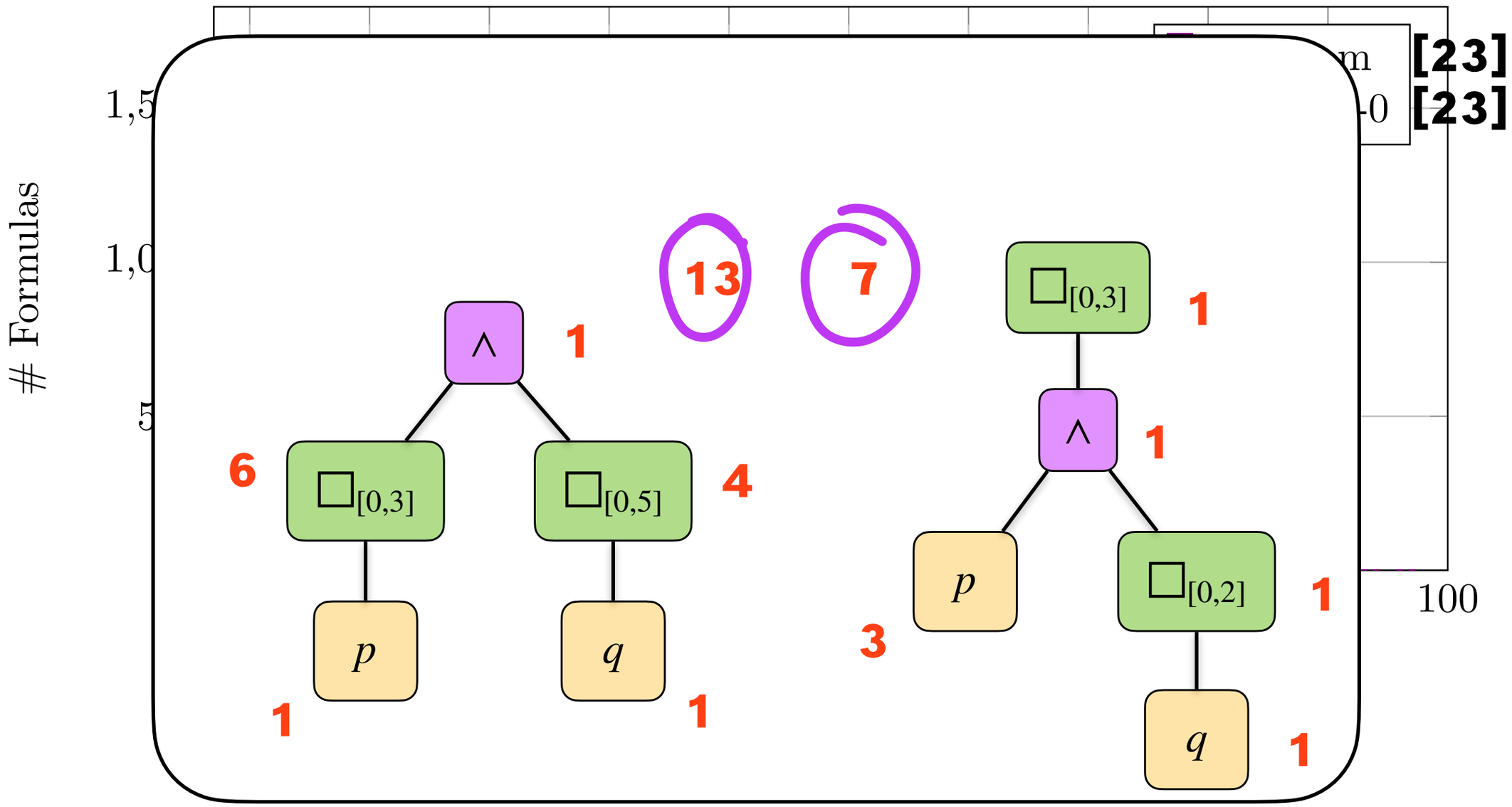
MLTL Equality Saturation Implementation



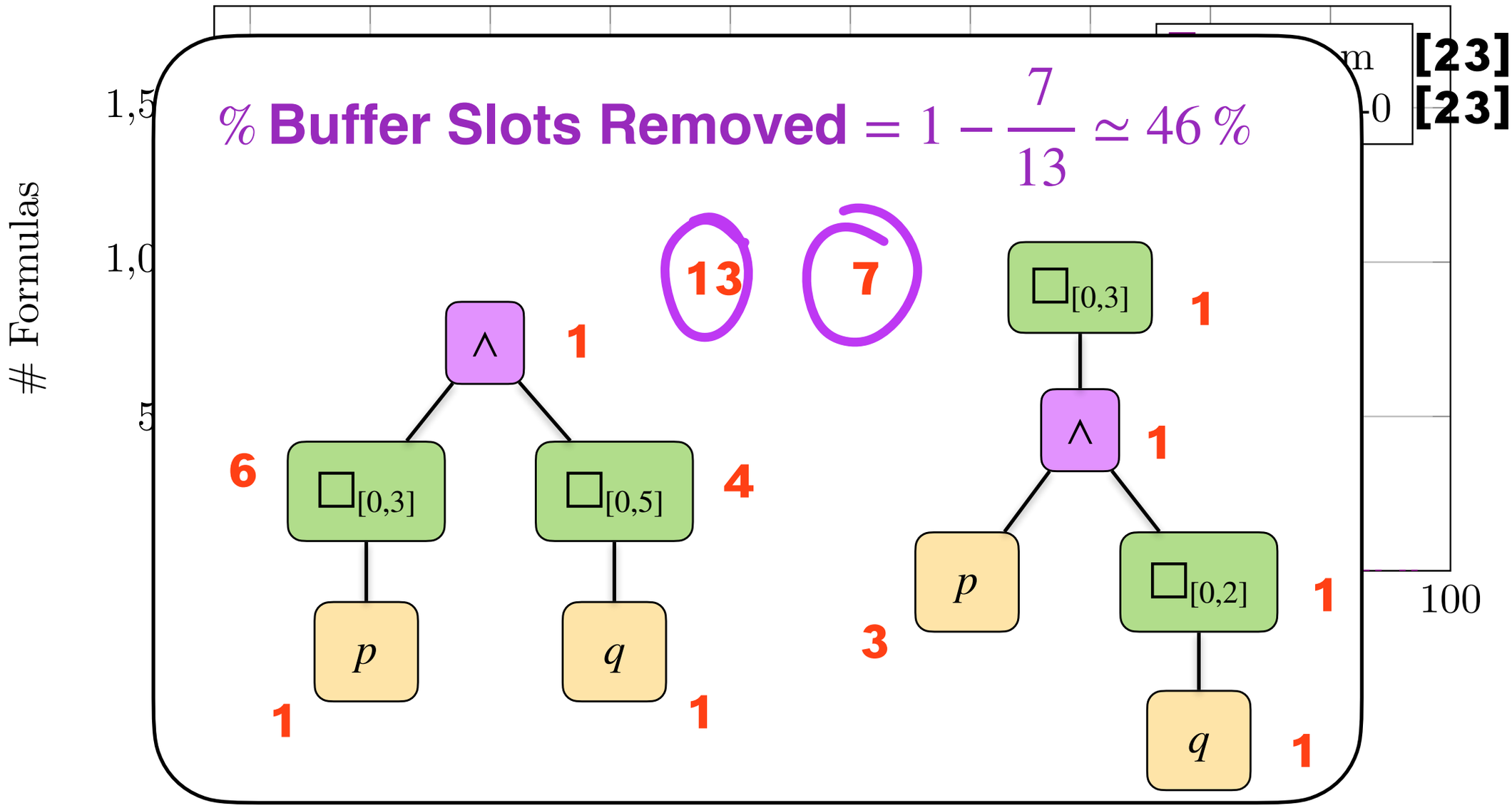
MLTL Equality Saturation Results (Random)



MLTL Equality Saturation Results (Random)



MLTL Equality Saturation Results (Random)



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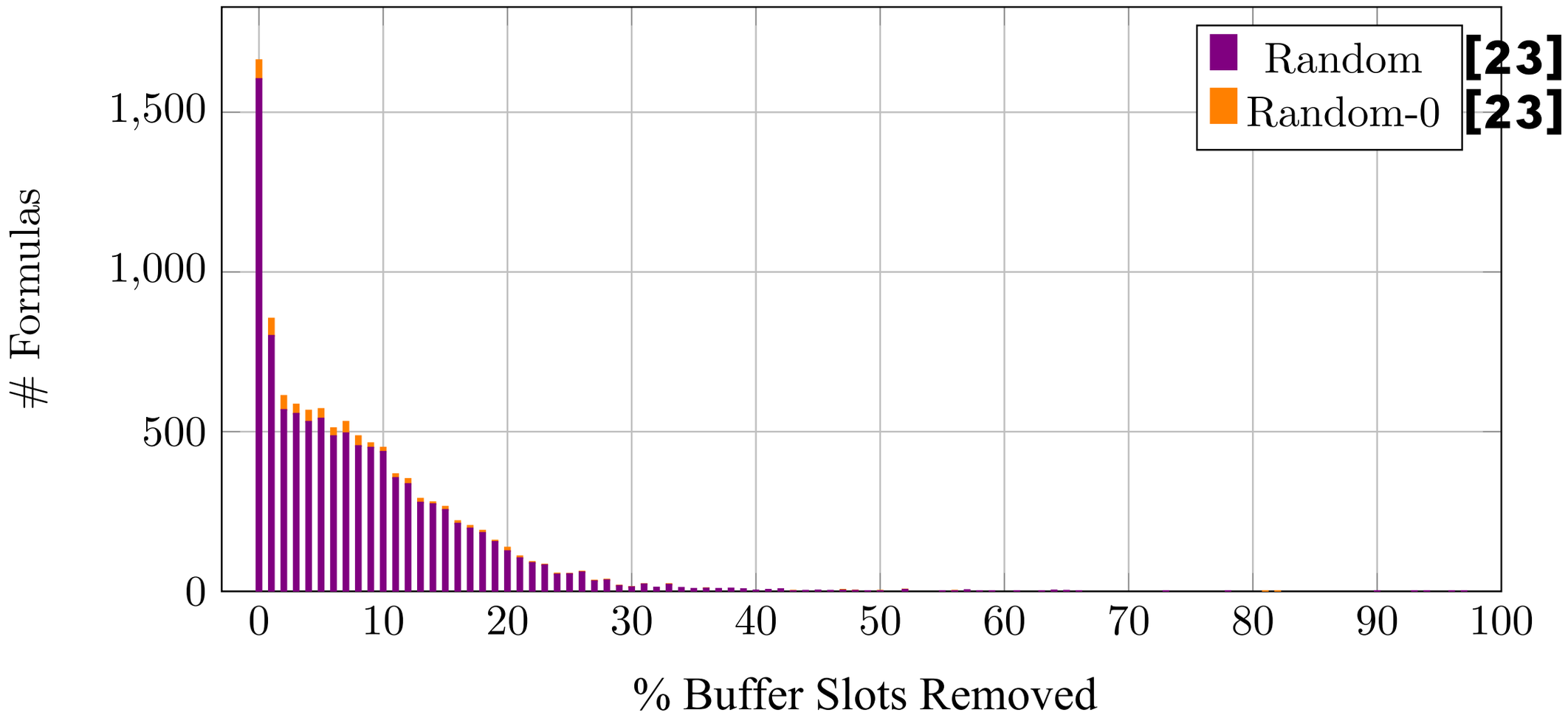
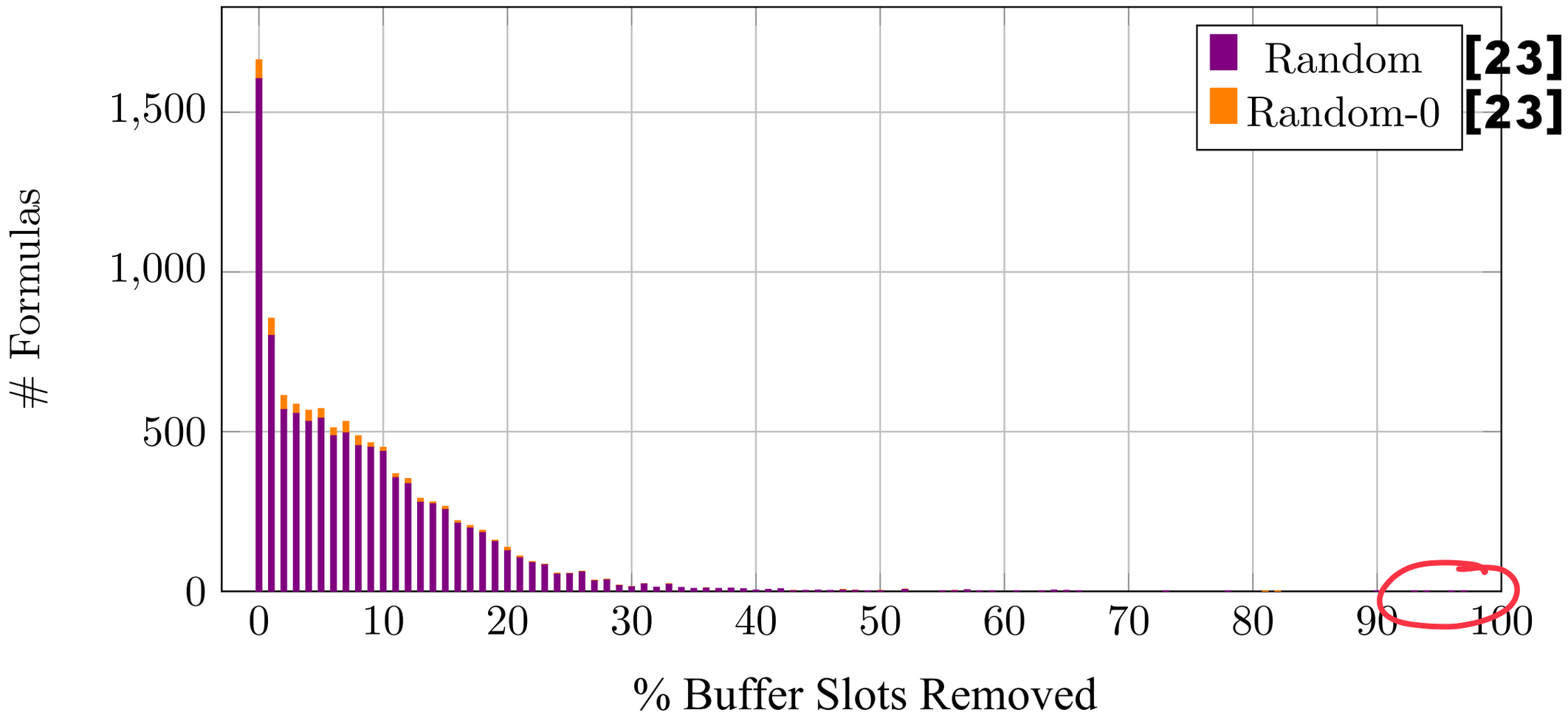
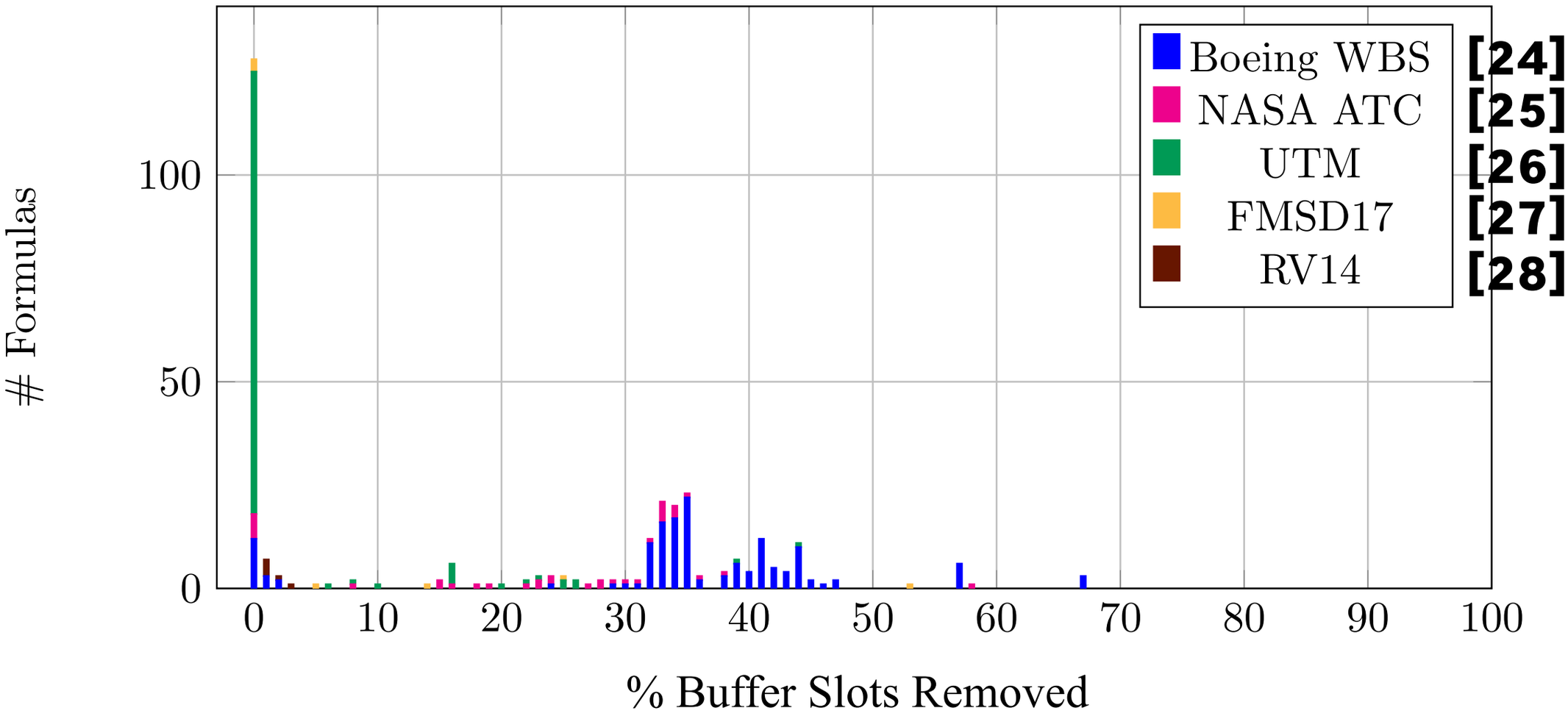


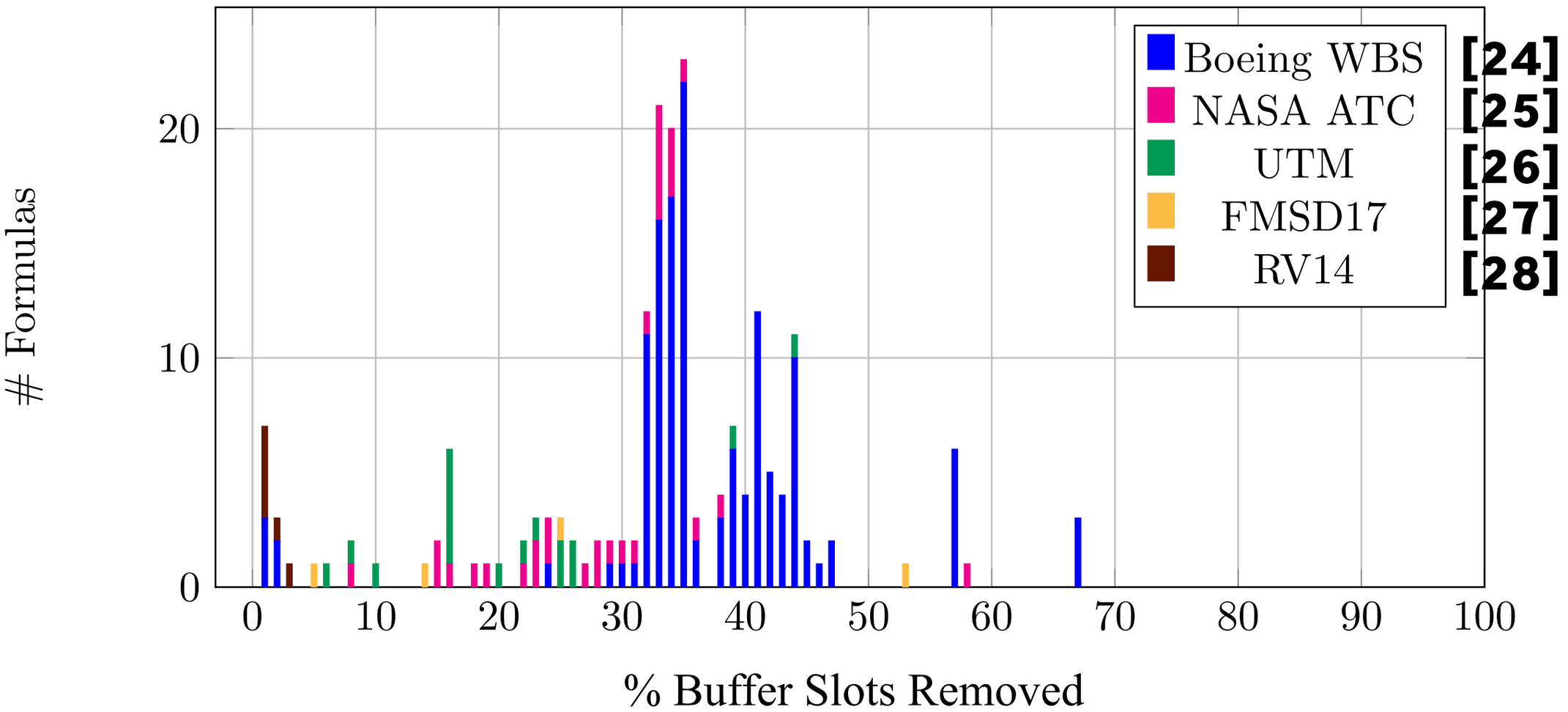
MLTL Equality Saturation Results (Random)



MLTL Equality Saturation Results (Human Authored)



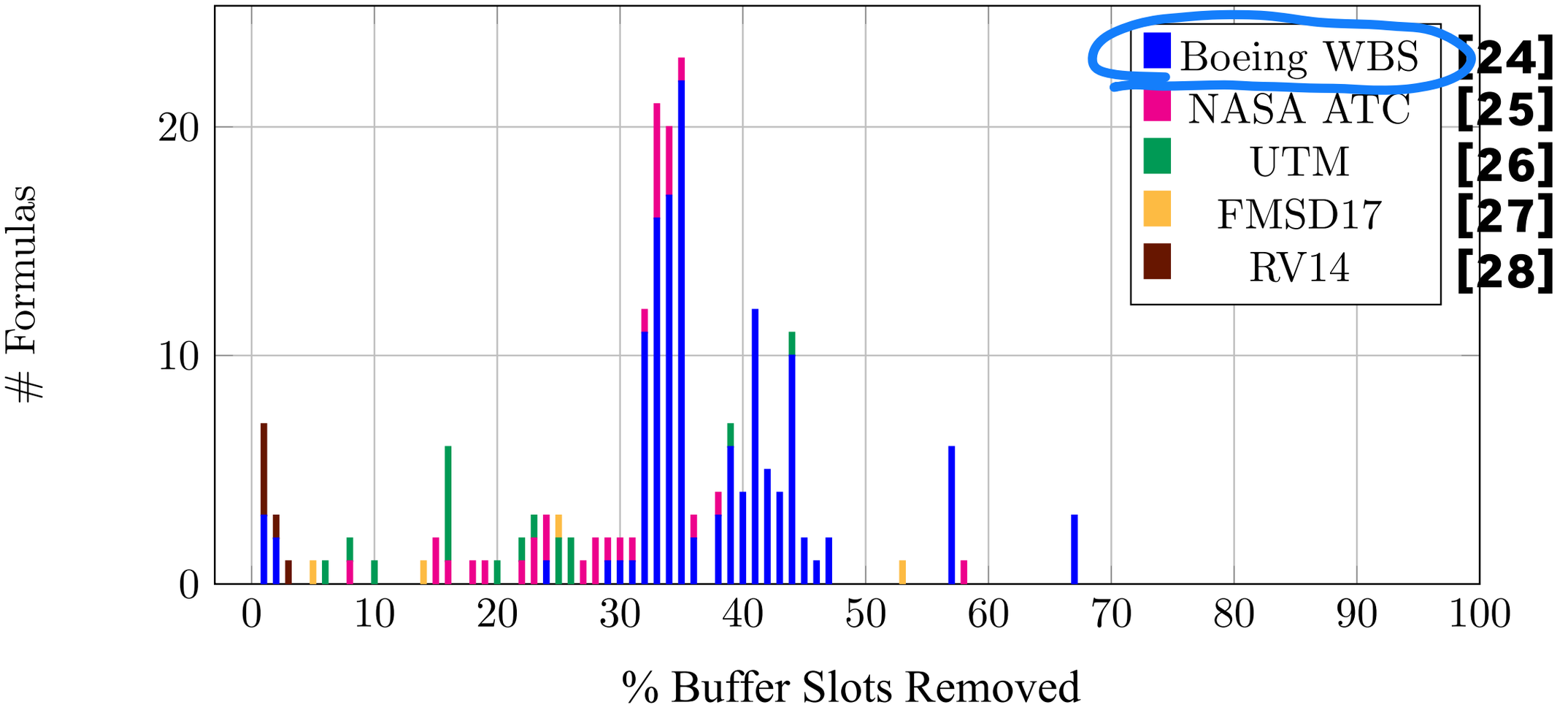
MLTL Equality Saturation Results (Human Authored)



***** < 1% reduction omitted**

MLTL Equality Saturation Results (Human Authored)

~35% Average Reduction



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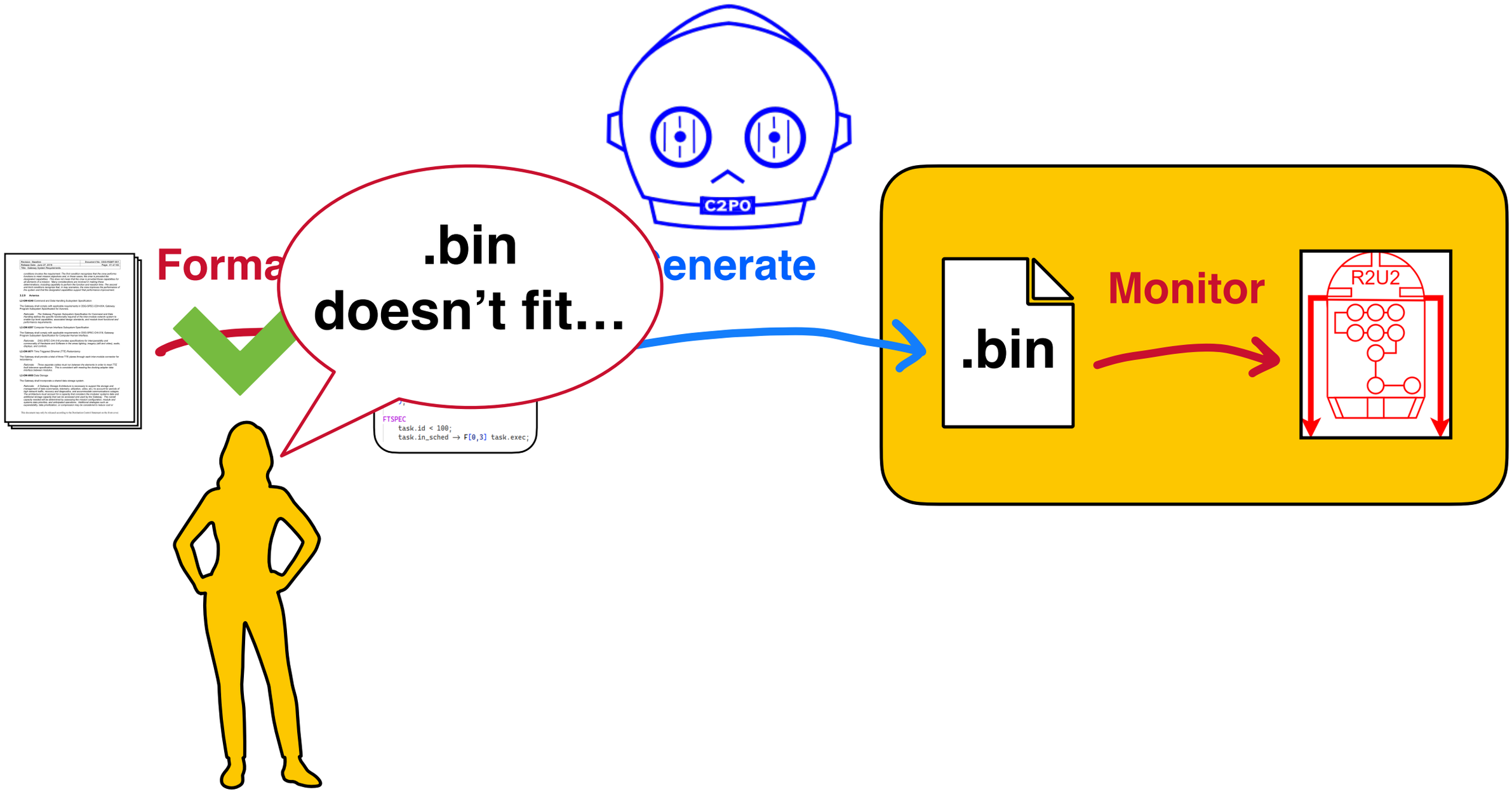
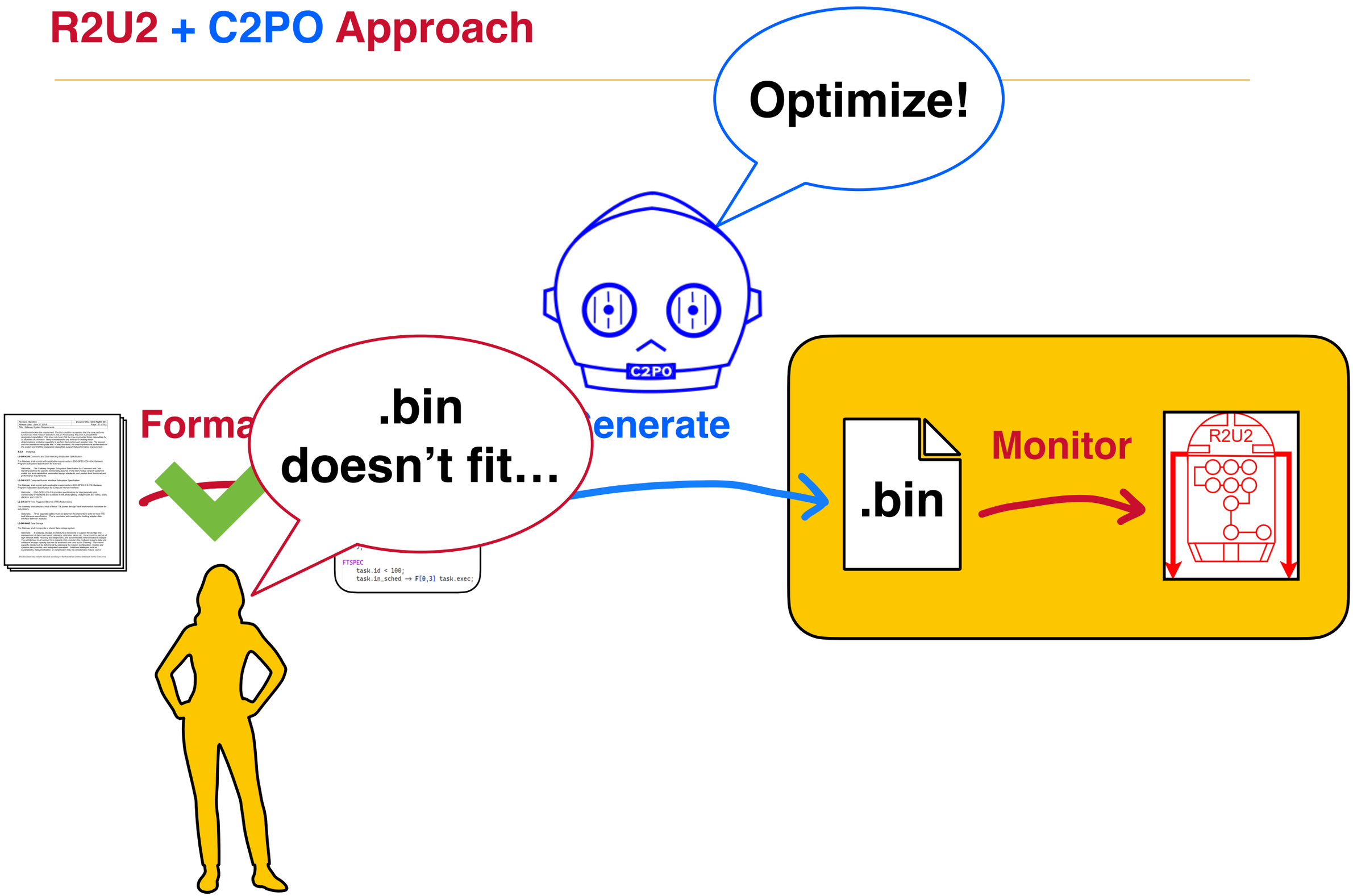
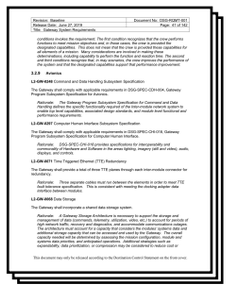
R2U2 + C2PO Approach



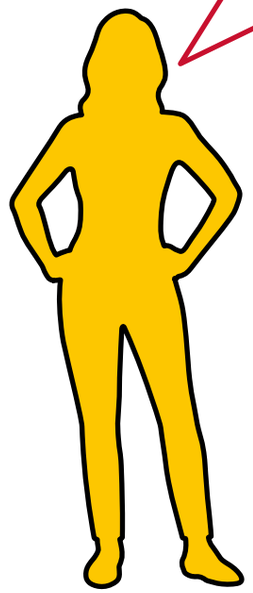
R2U2 + C2PO Approach



R2U2 + C2PO Approach

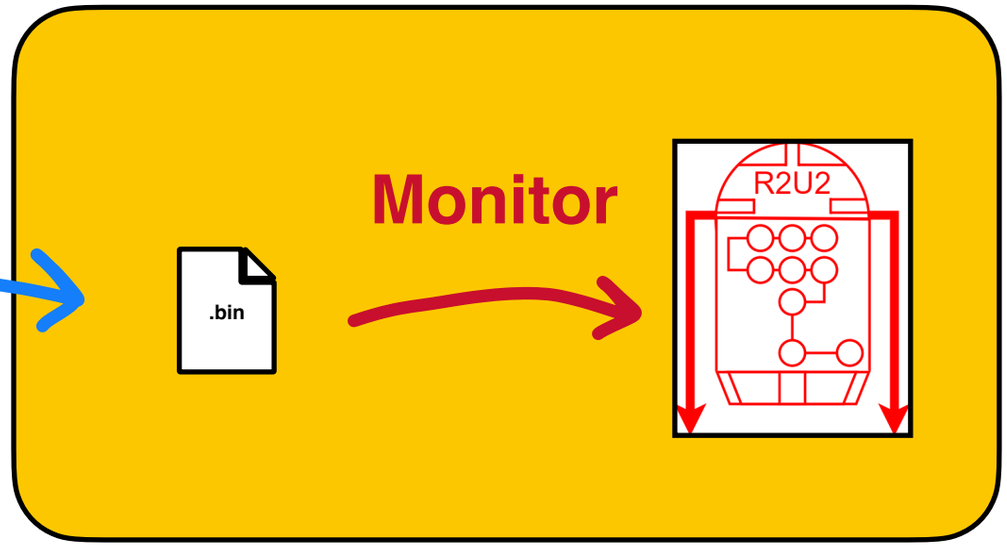


Forma

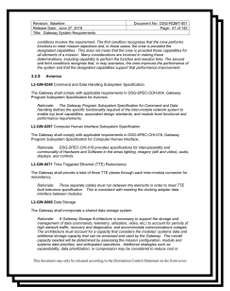


enerate


```
FTSPEC
    task.id < 100;
    task.in_sched → F[0,3] task.exec;
```



R2U2 + C2PO Approach



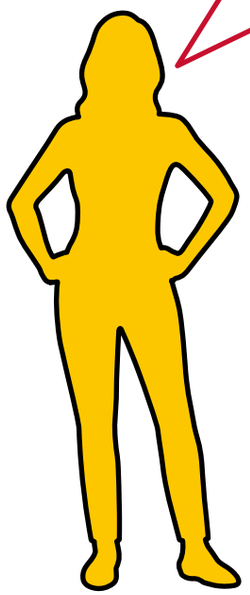
Forma

You're welcome!

Thanks, C2PO!

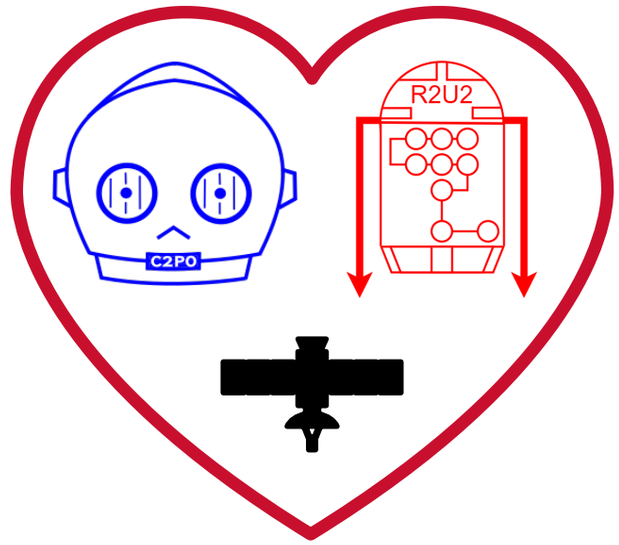
enerate

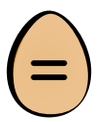
```
FTSPEC
    task.id < 100;
    task.in_sched → F[0,3] task.exec;
```



Questions?

- **C2PO**
  - Optimized encoding of MLTL monitors for R2U2
- FO-MLTL
  - First-order MLTL over bounded dynamic sets
- **MLTL Optimizations**
  - Rewrite Rules
  - Equality saturation via EggLog
- **Future Directions**
  - Implement FO-MLTL in R2U2
  - More rewrites!





r2u2.temporallogic.org

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