Temporal Safety Proofs for Systems Code

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Based on the following papers:

- Lazy Abstraction, POPL'02, Jan 2002
- Temporal Safety Proofs for Systems Code, CAV'02, July 2002

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Outline

1. Introduction
2. Predicate Abstraction
3. Lazy Abstraction
4. Proof Generation
5. Experiments
6. Conclusion and Future Work

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- We focus on:
  - safety properties
    - locking displines, interface specifications
  - software written in C
    - Linux & Windows NT device drivers

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  - doesn't scale to low-level implementations
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- Verification using abstraction – refinement based techniques
  - automatic construction and verification of abstract models
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  - lazy abstraction (non uniform abstraction)
- Certification: proof-carrying code
  - verification condition computed from the abstract reachability set
  - proof generation using internal data from verification
  - small correctness certificates

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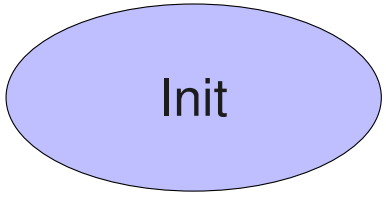

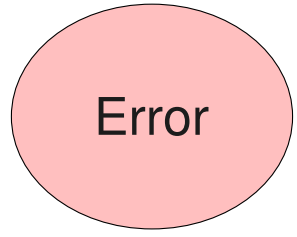

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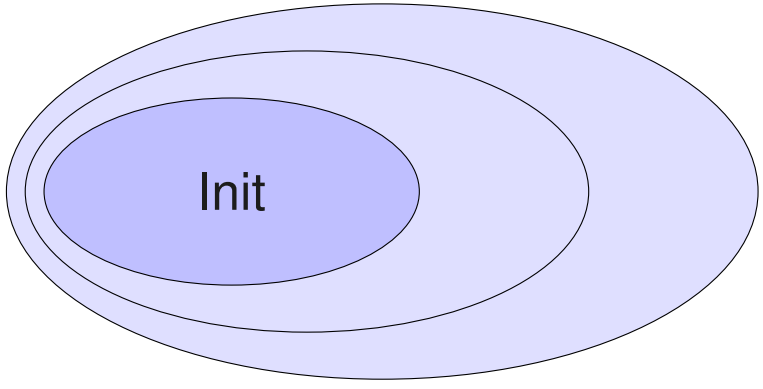

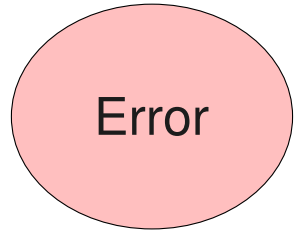

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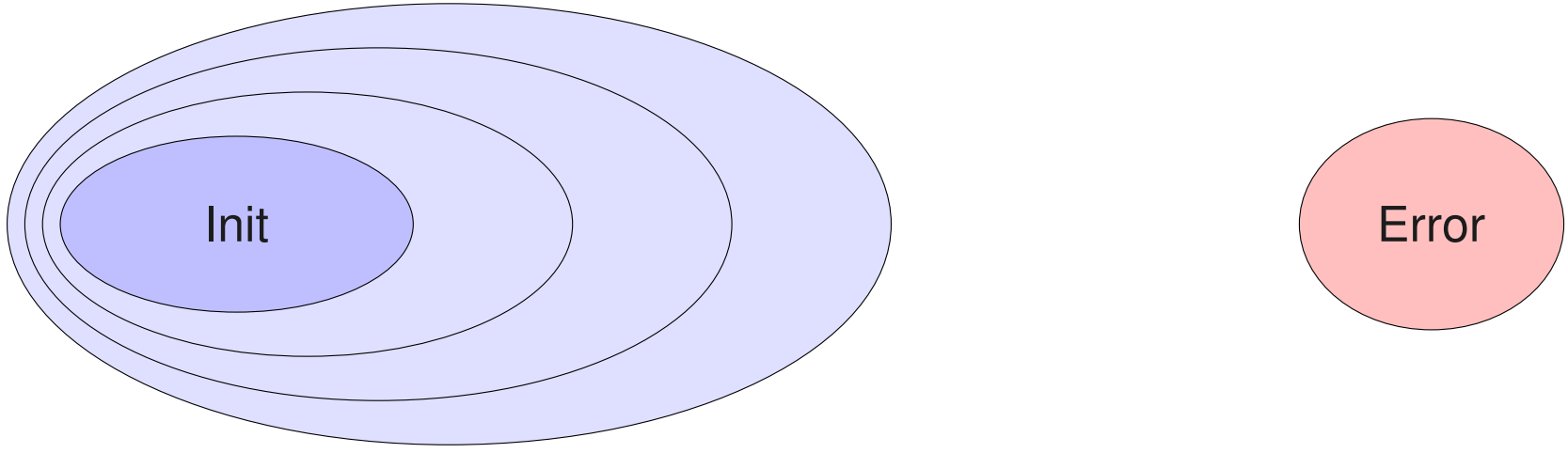

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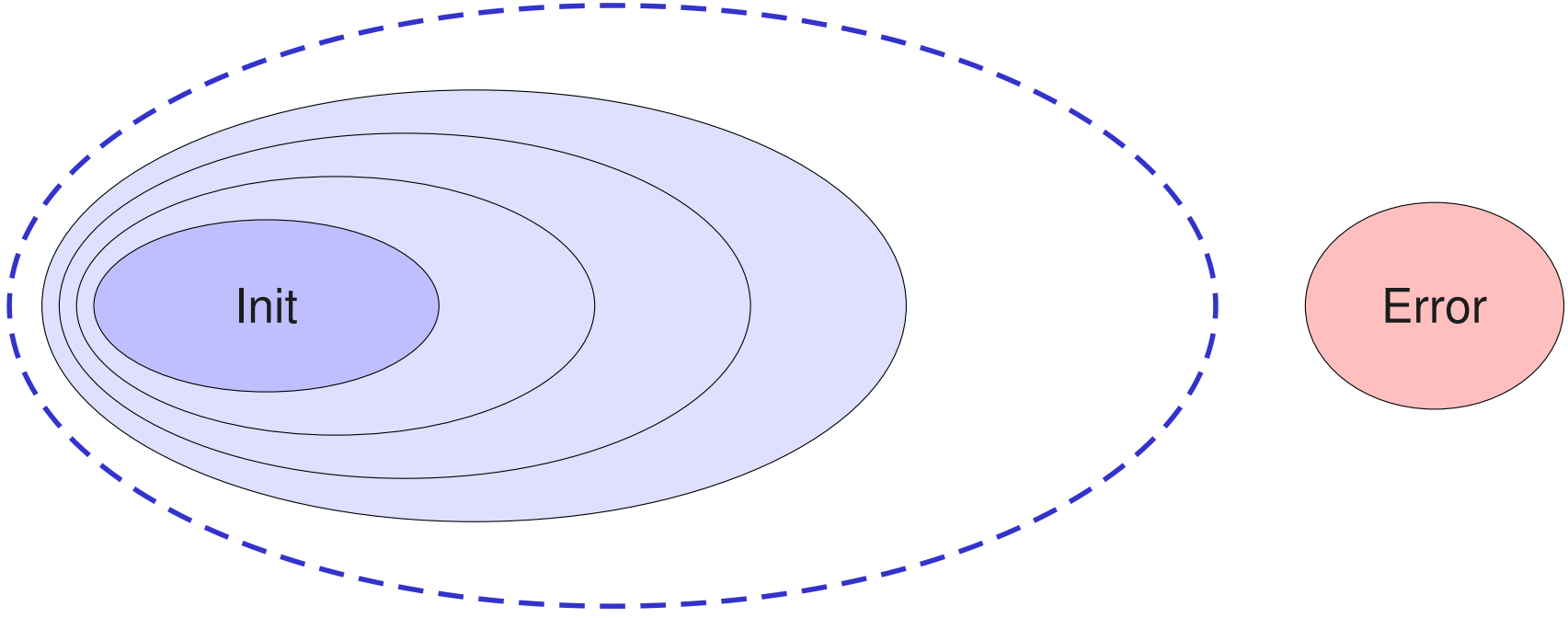

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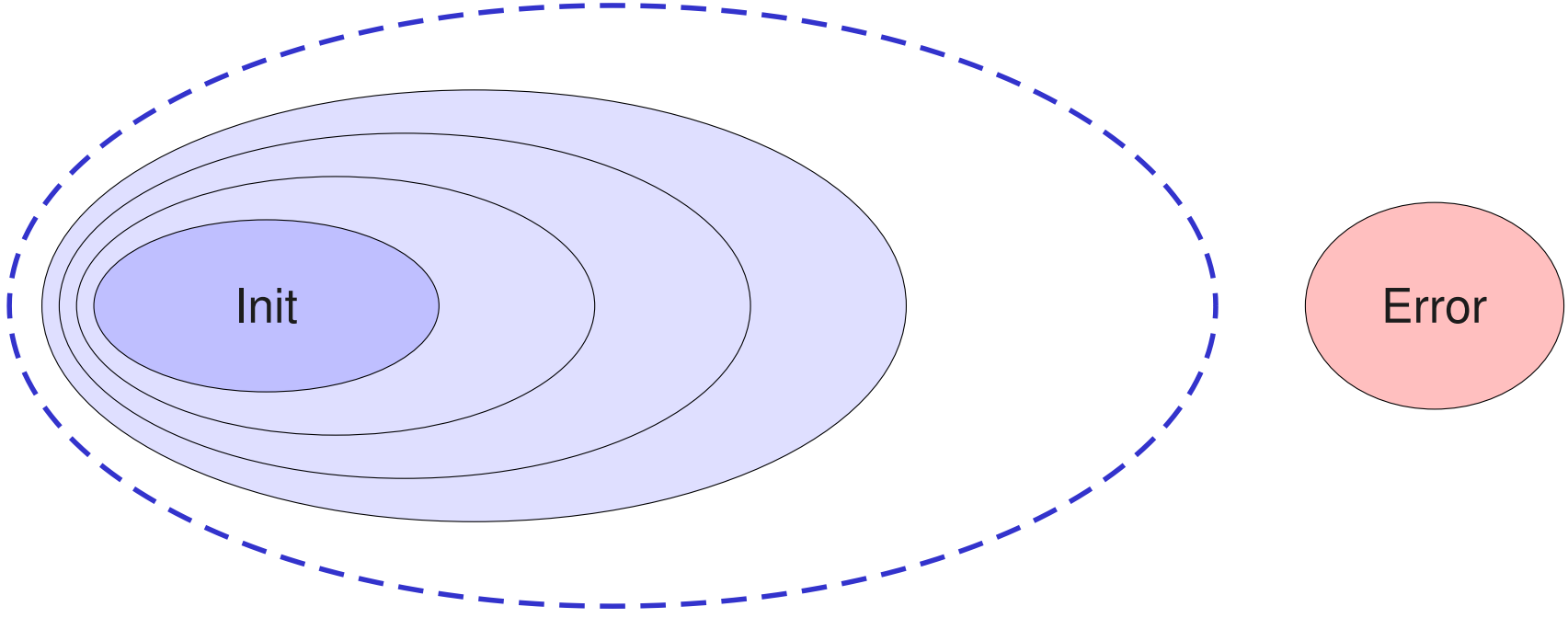

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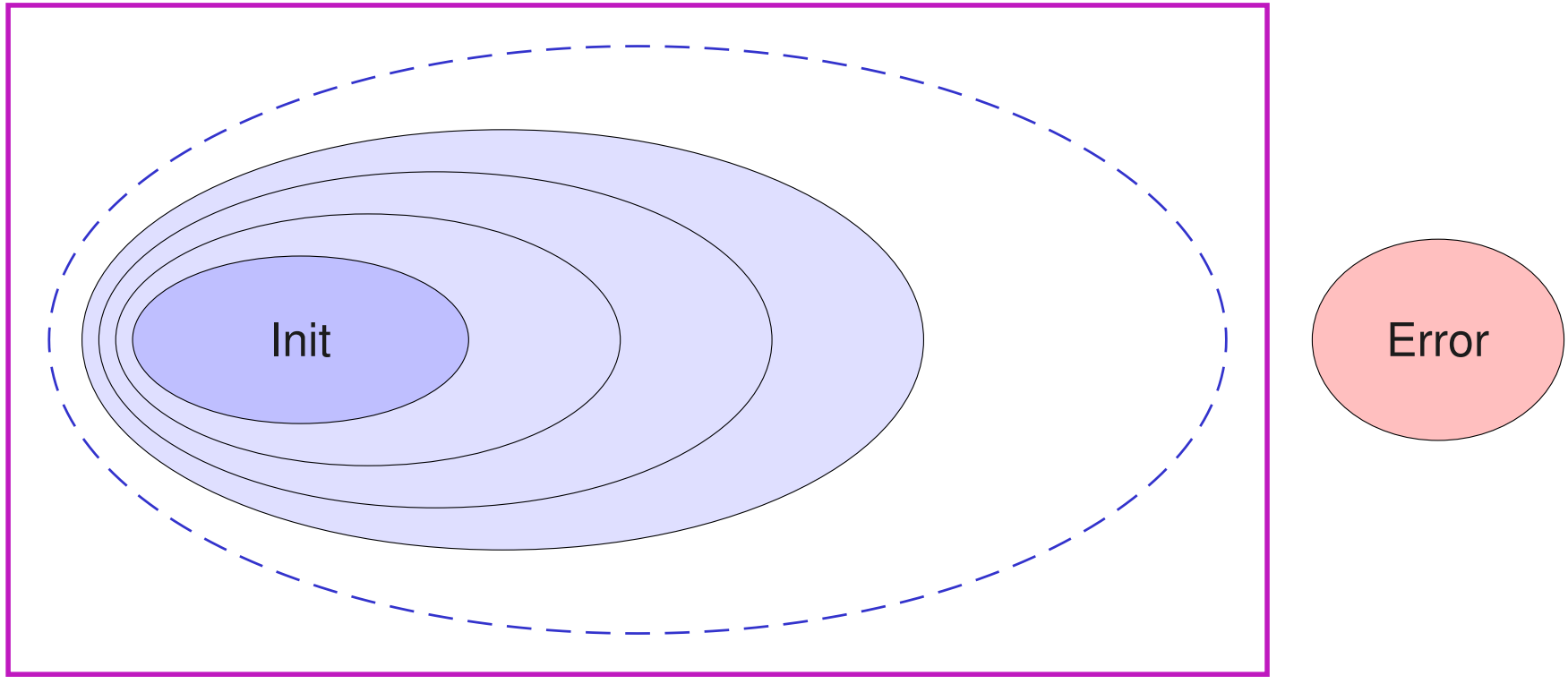

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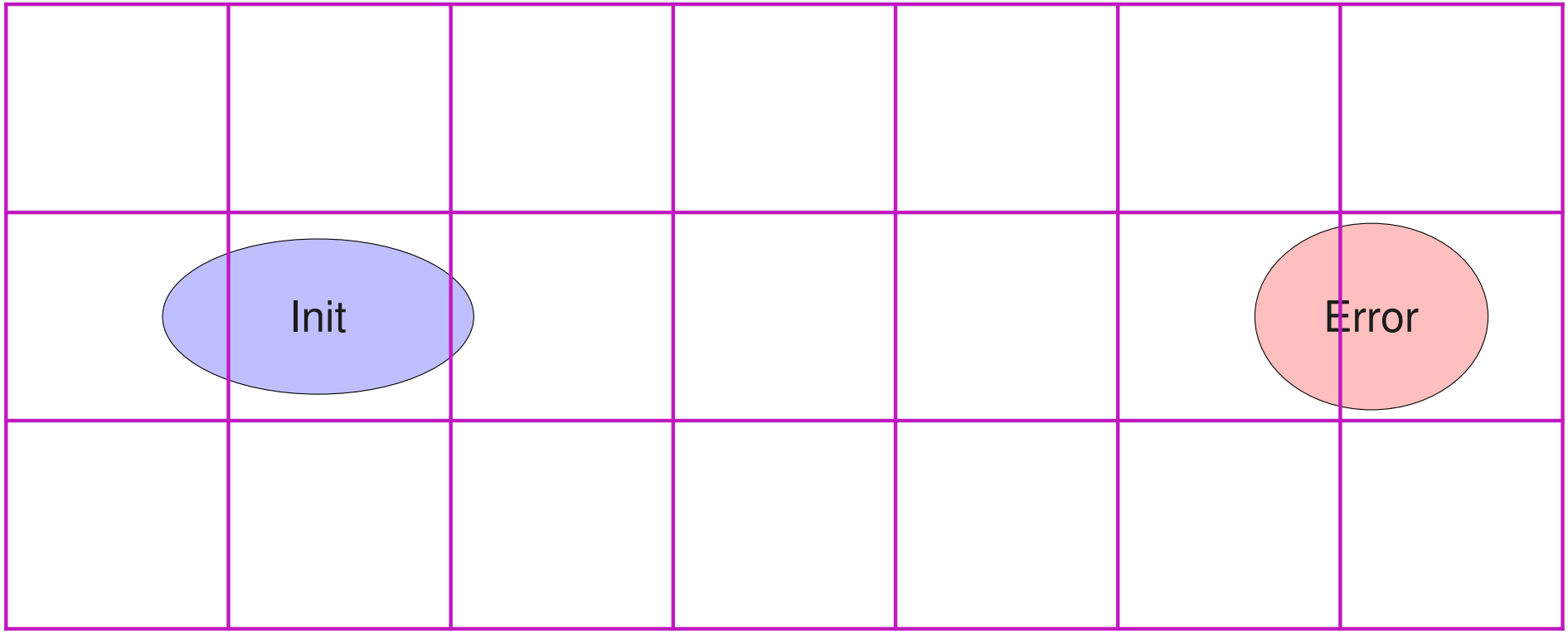

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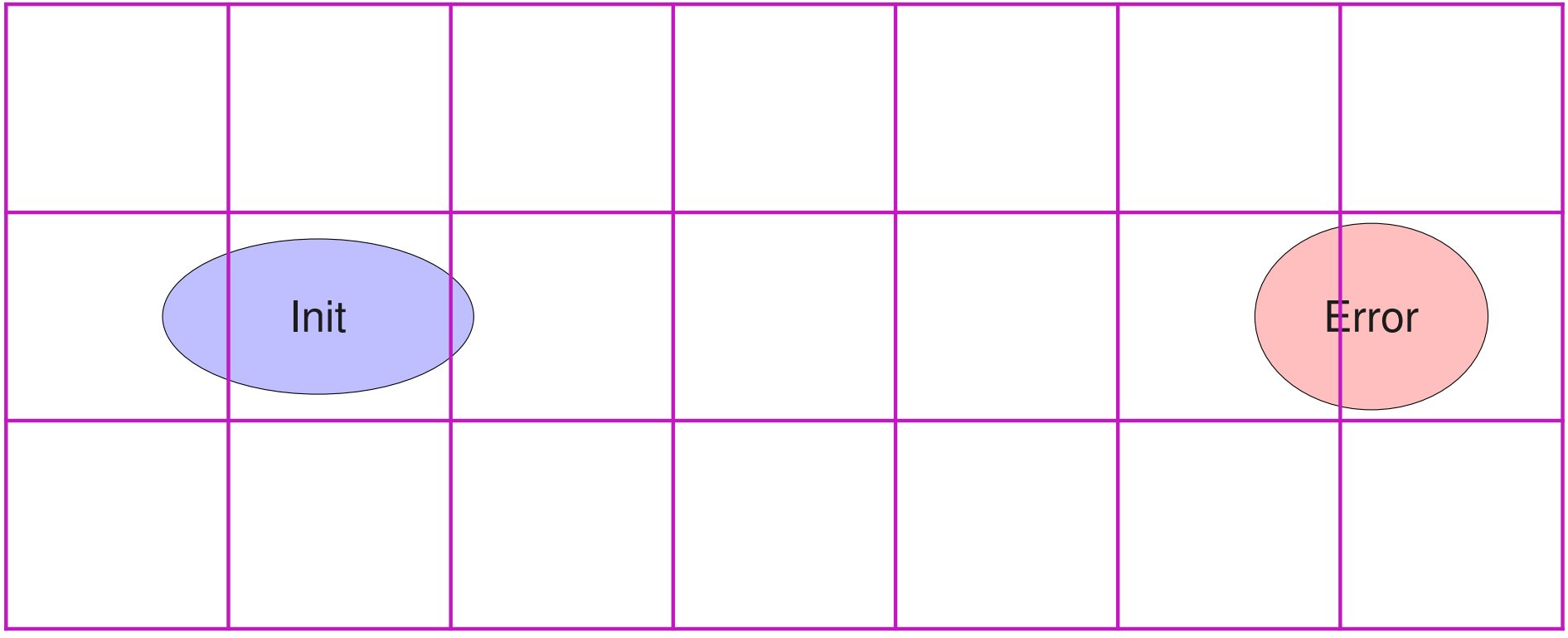

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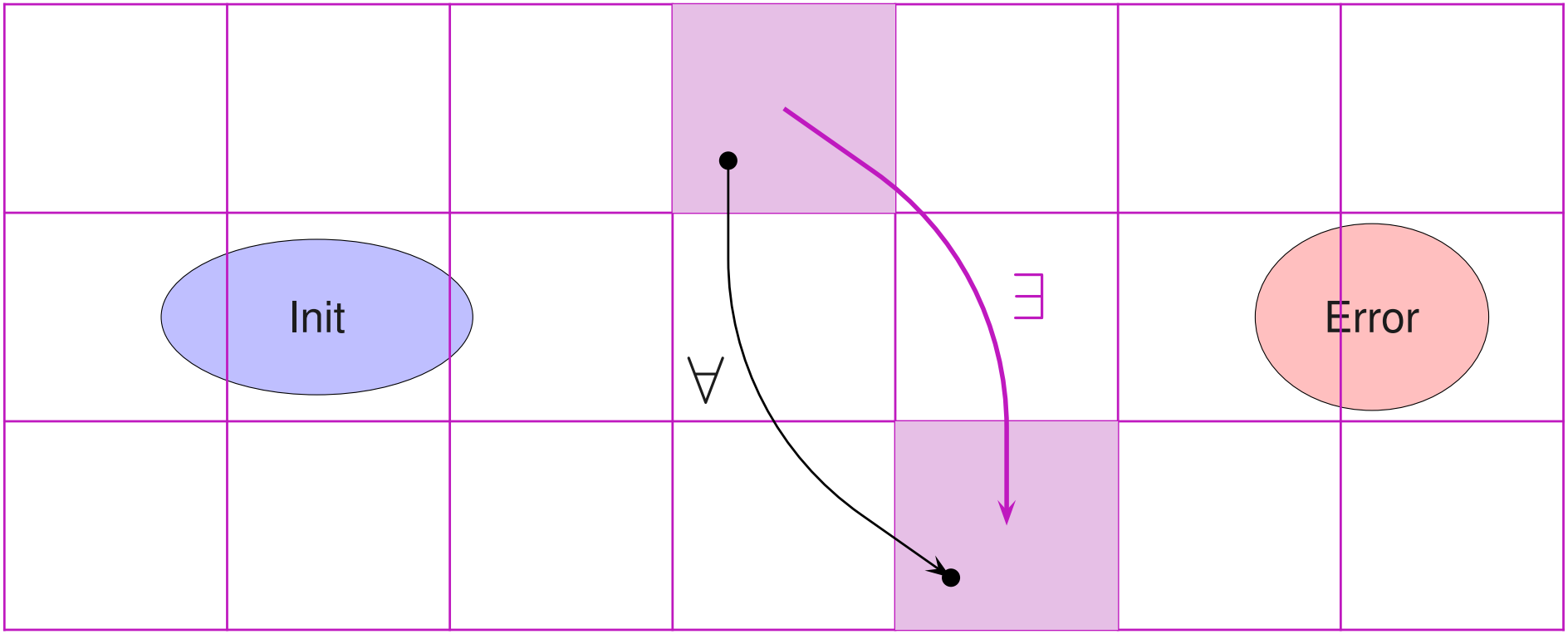

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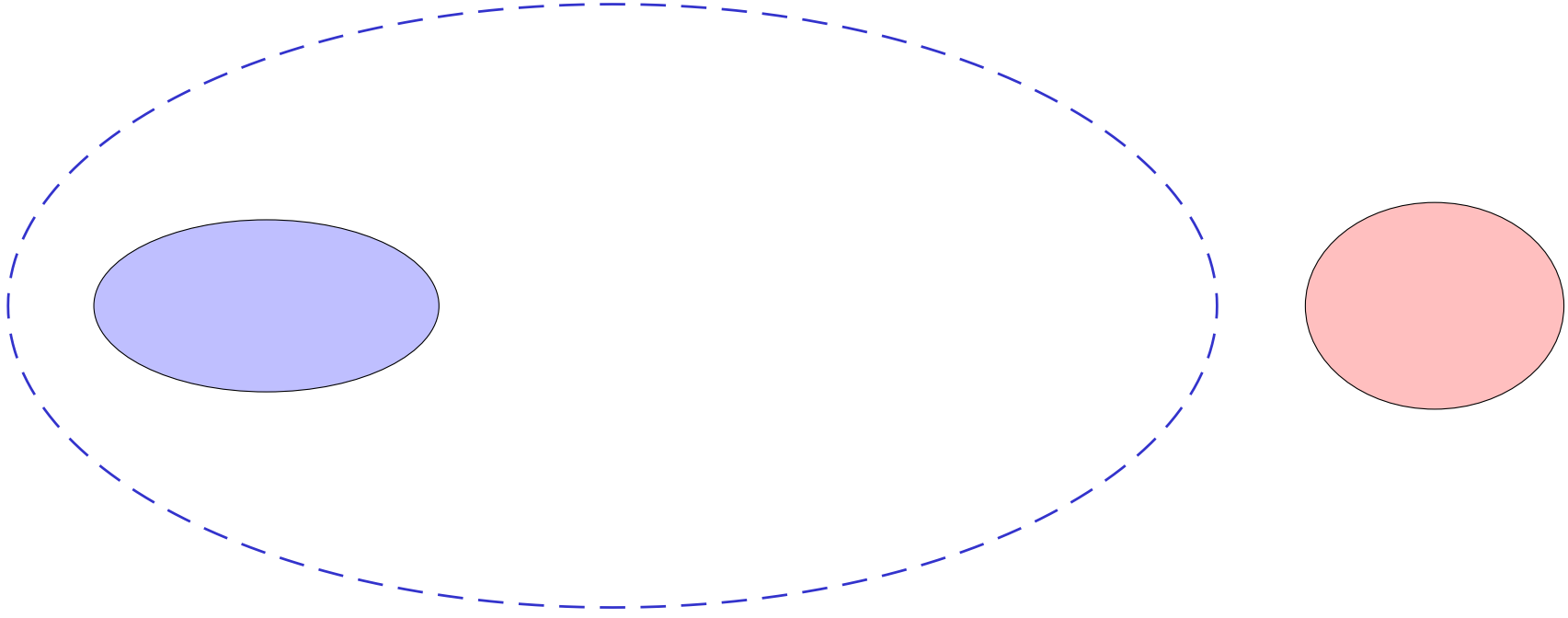
- Conservative abstraction (computed using decision procedures)

Model-Checking with Predicate Abstraction



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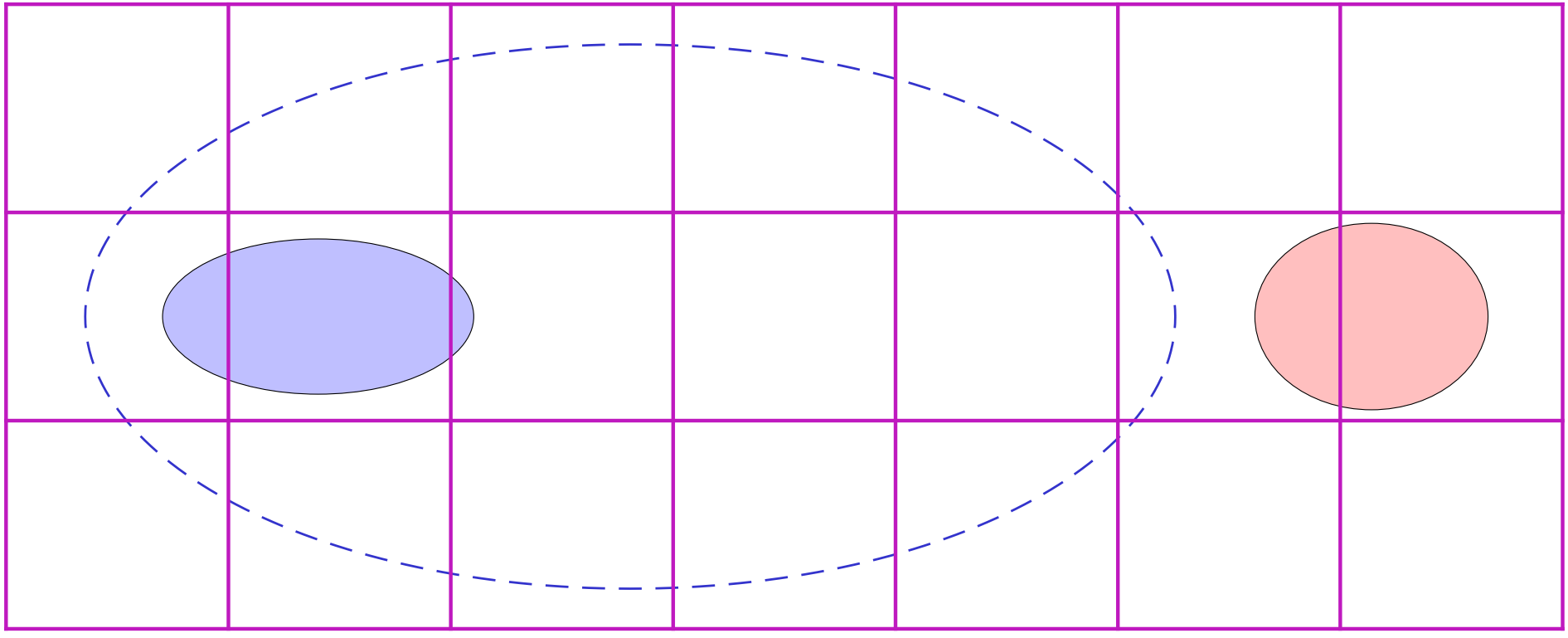

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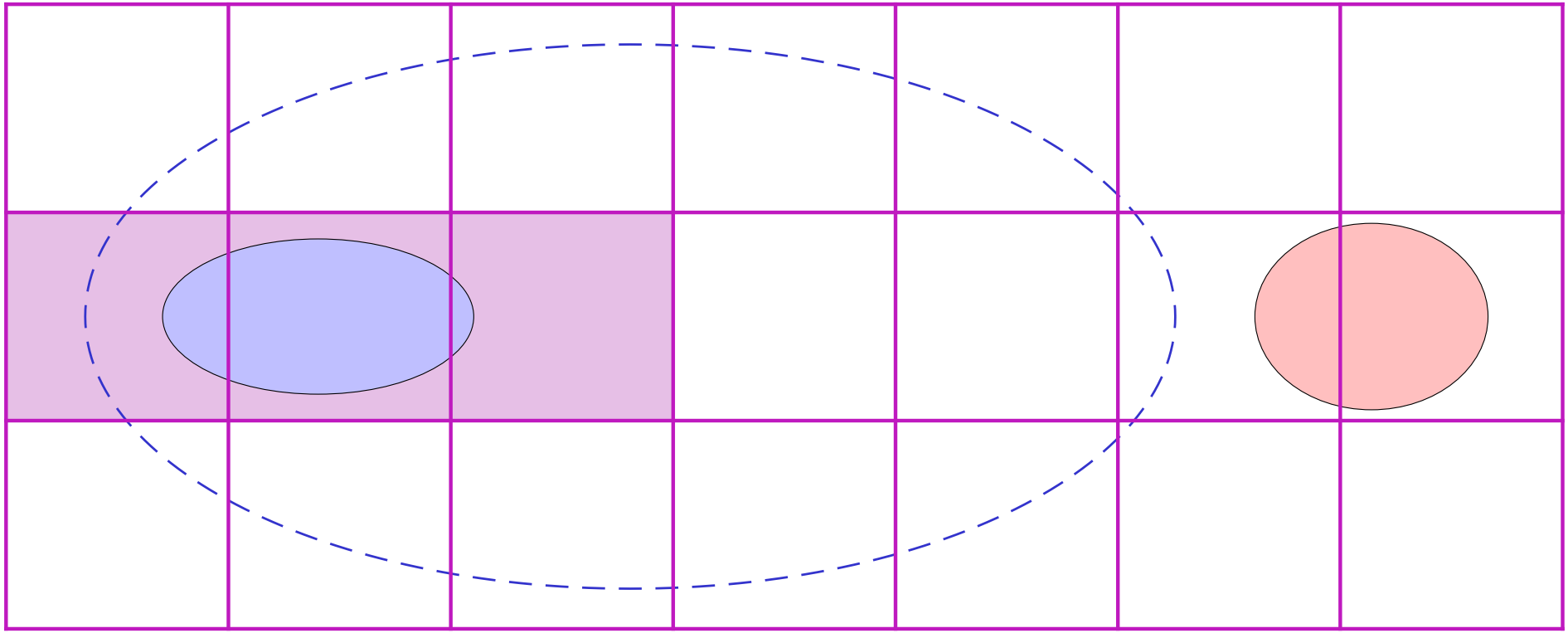

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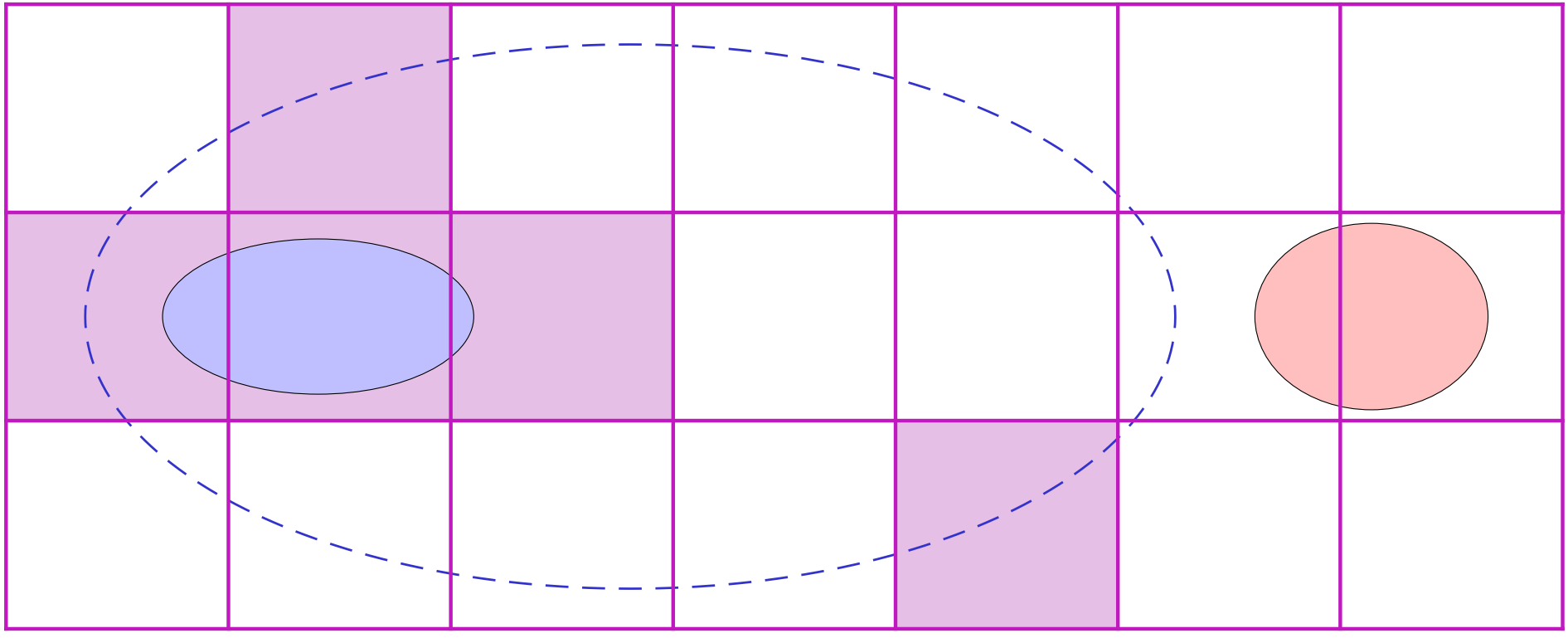

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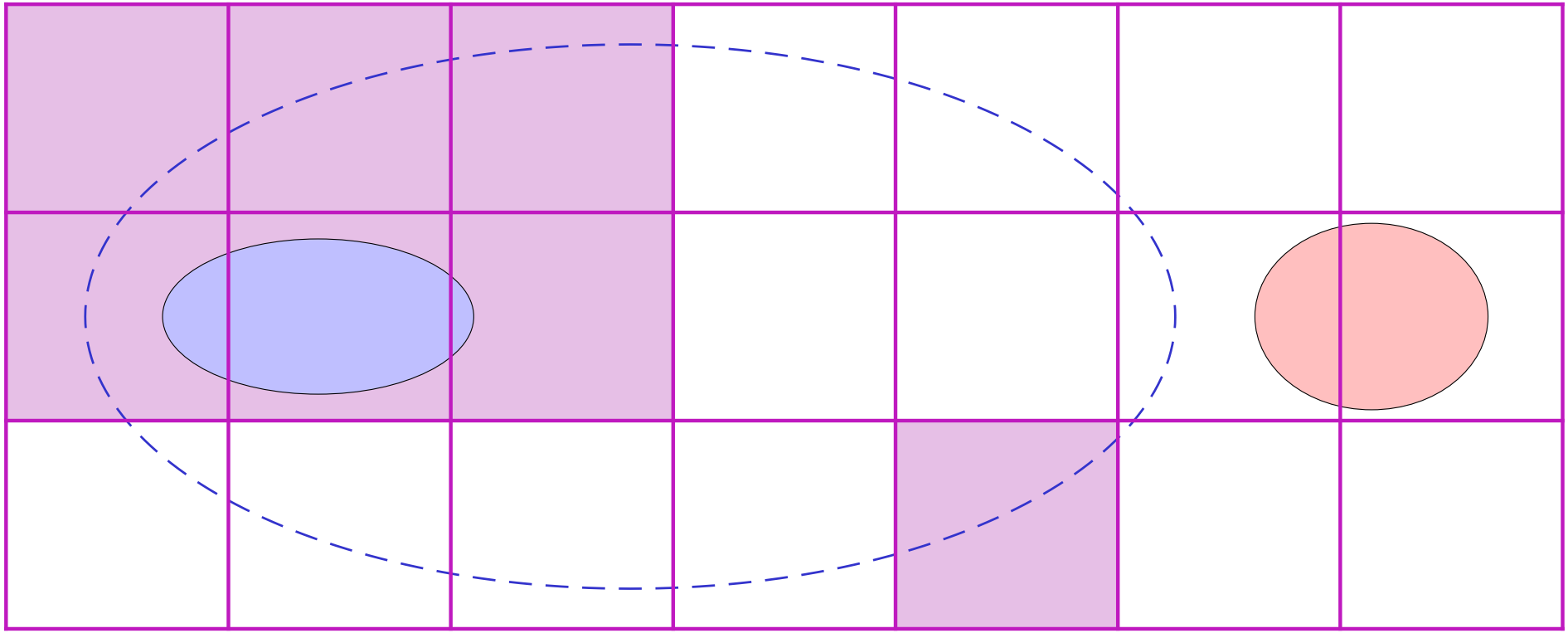

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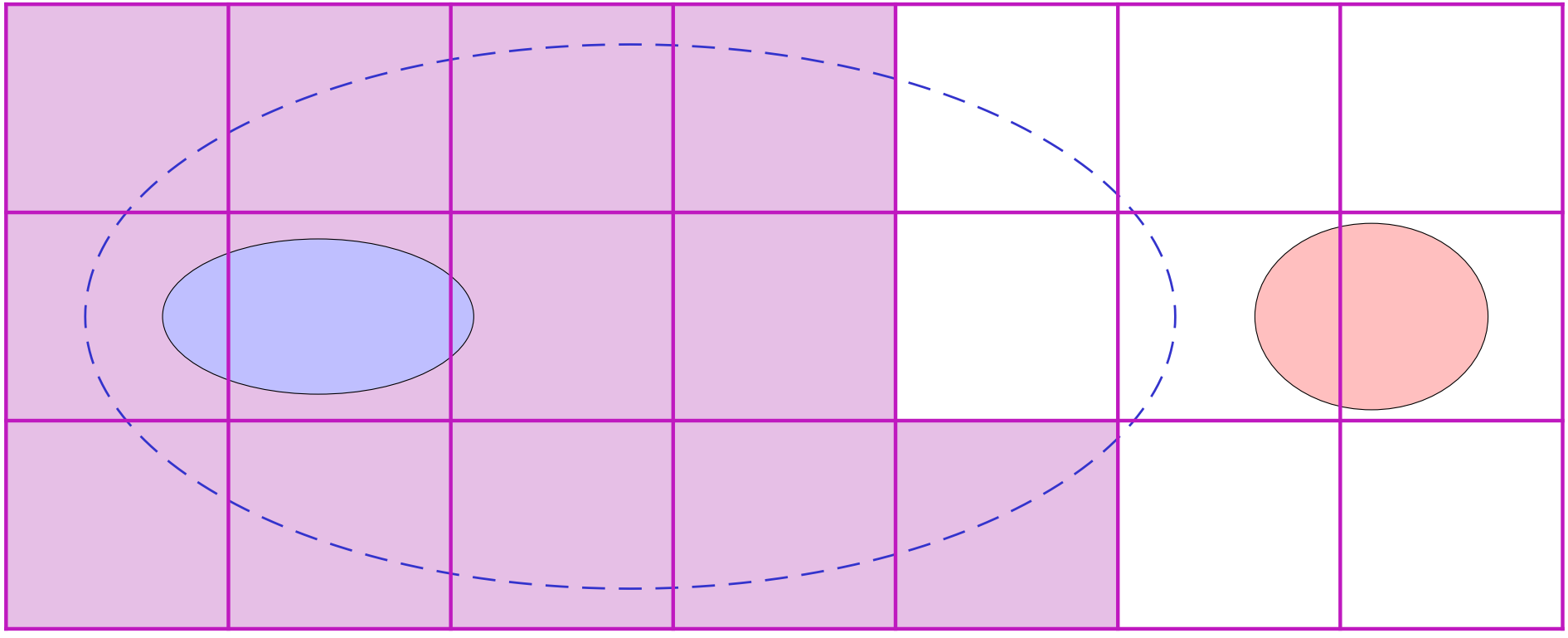

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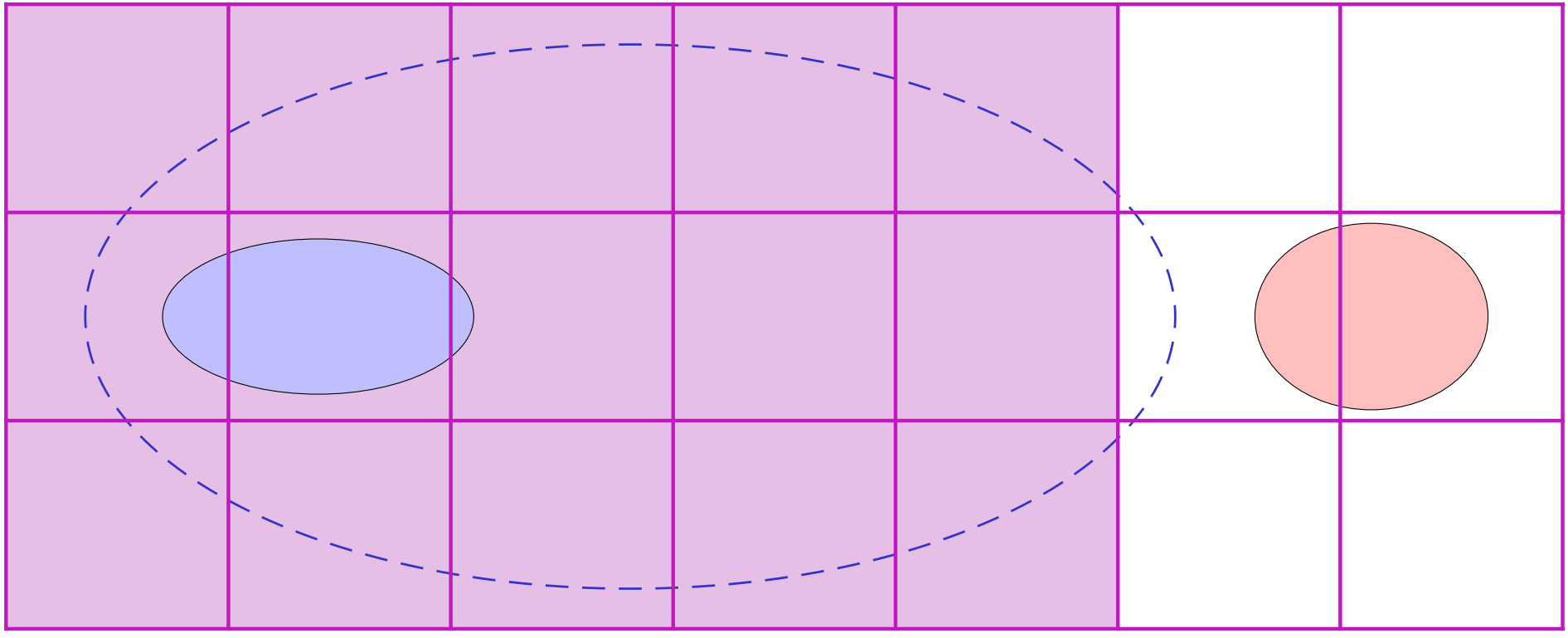

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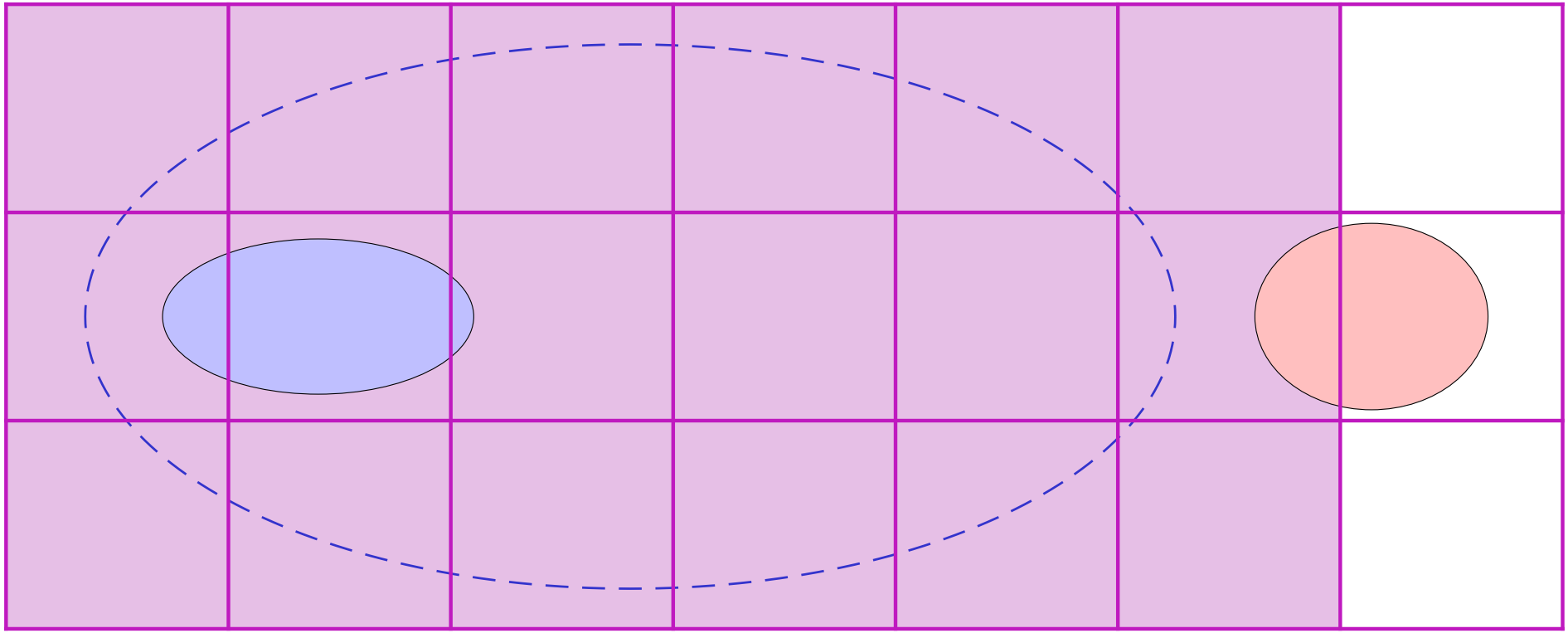

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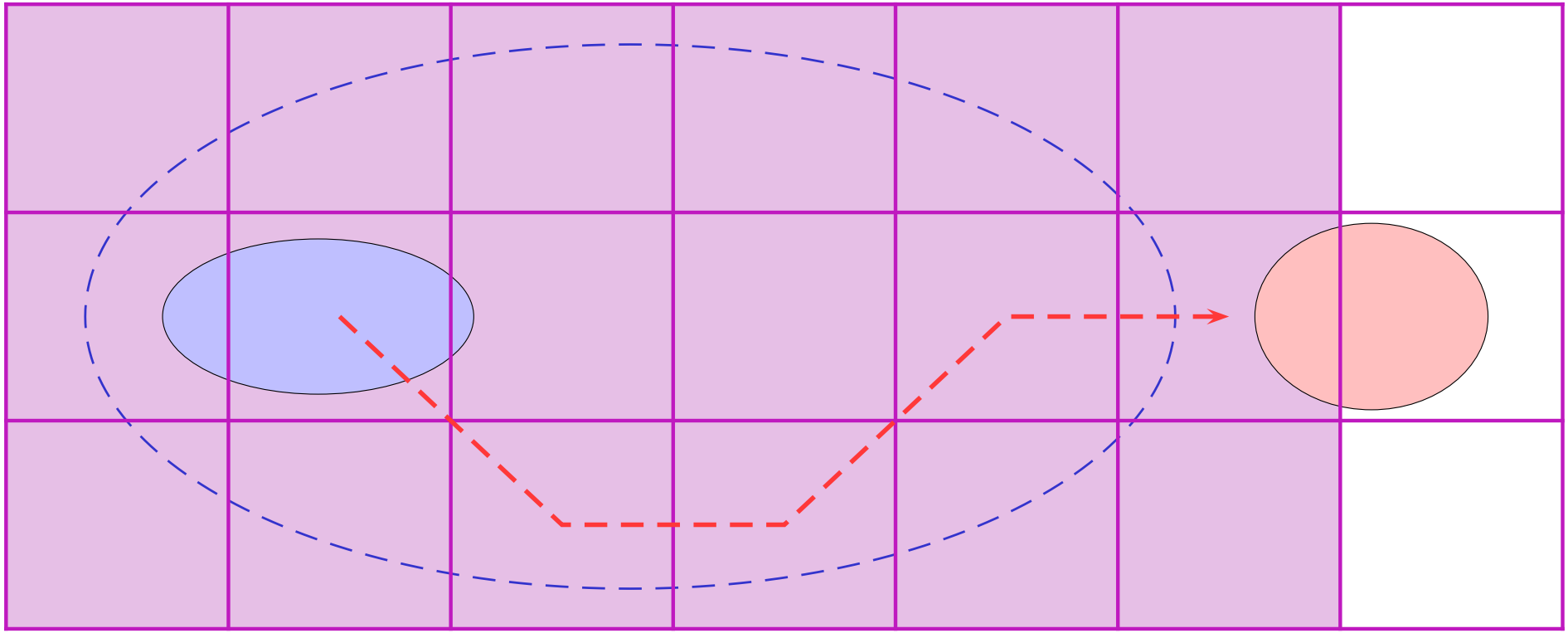

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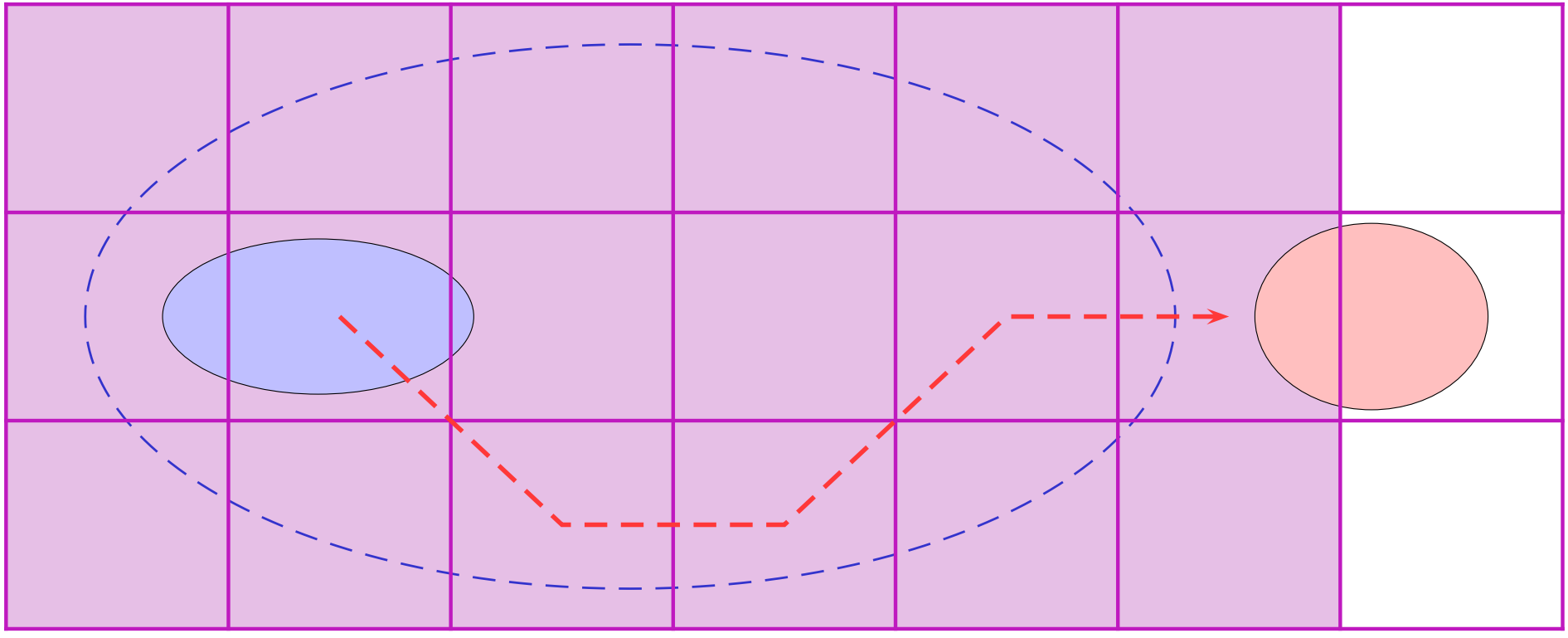
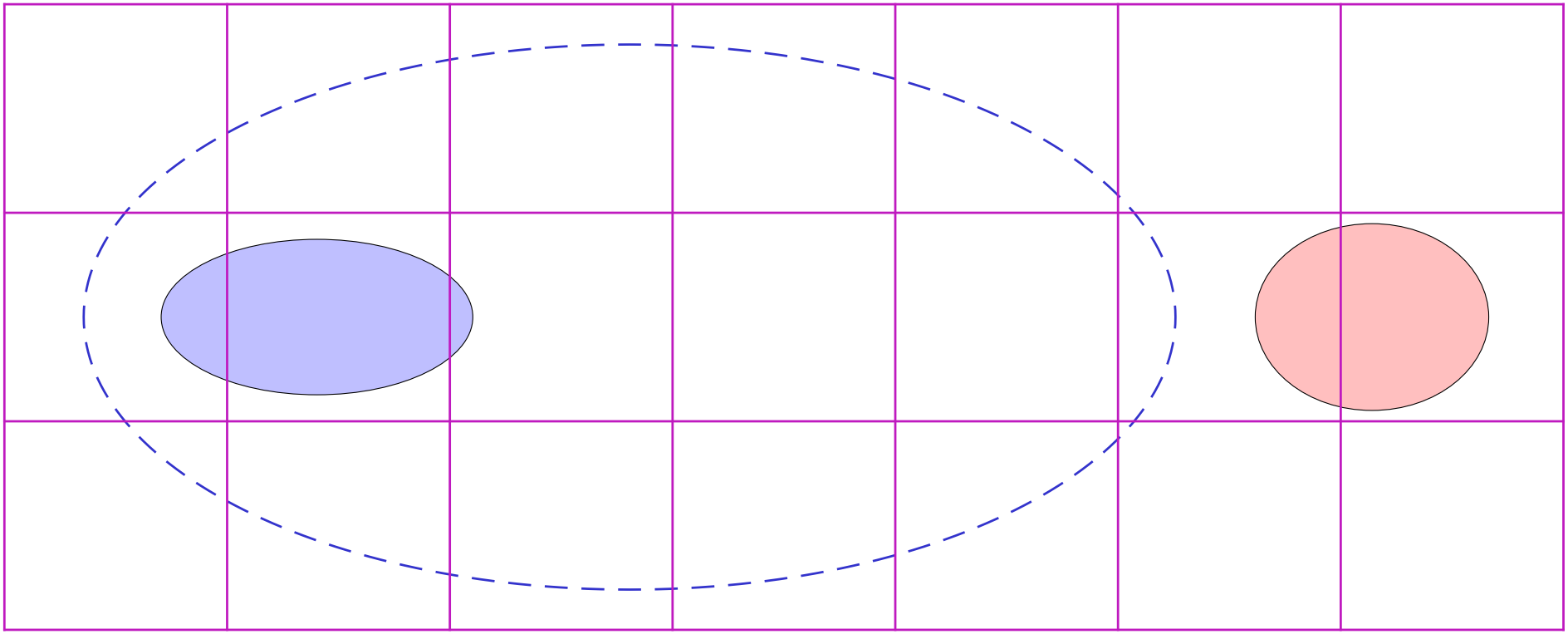


- Abstraction too coarse
- Refinement is needed to avoid this spurious error trace
  - split boxes into smaller ones: add new predicates

Refinement with Predicate Abstraction



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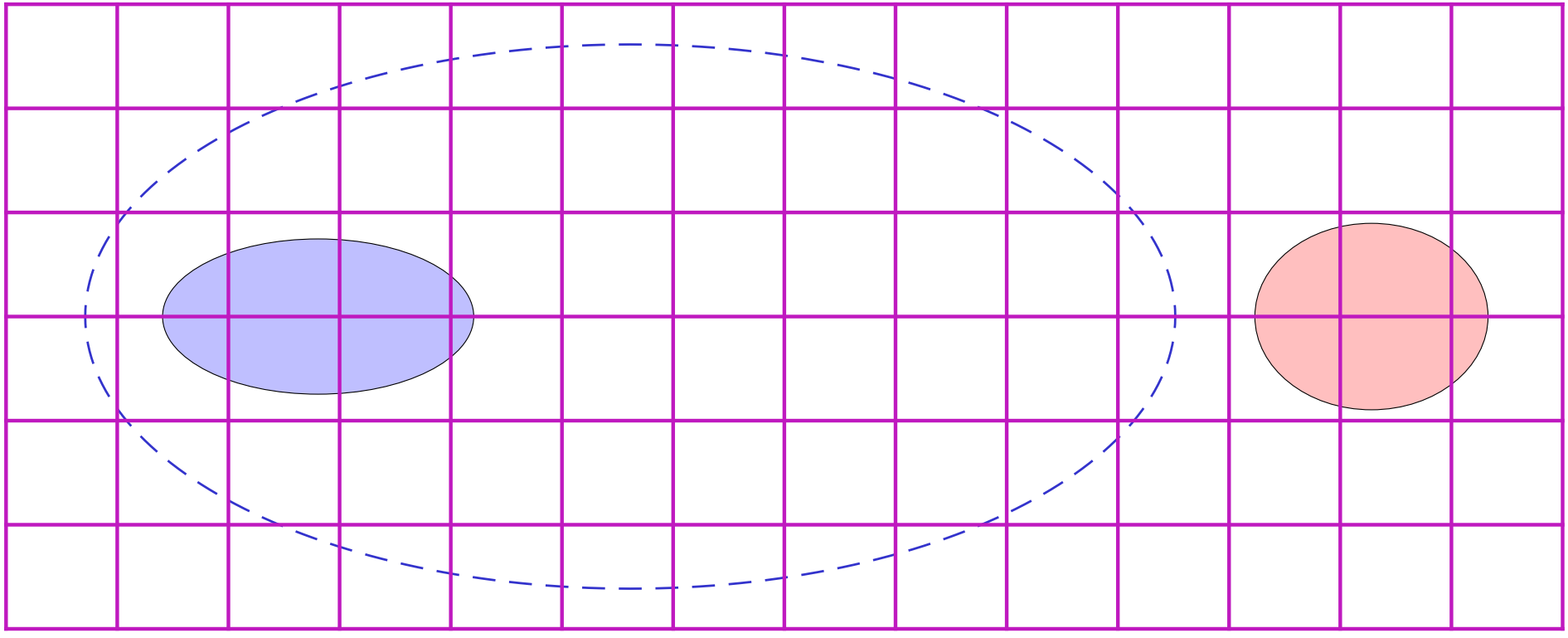

- Refinement: adding new predicates
- Finer grid

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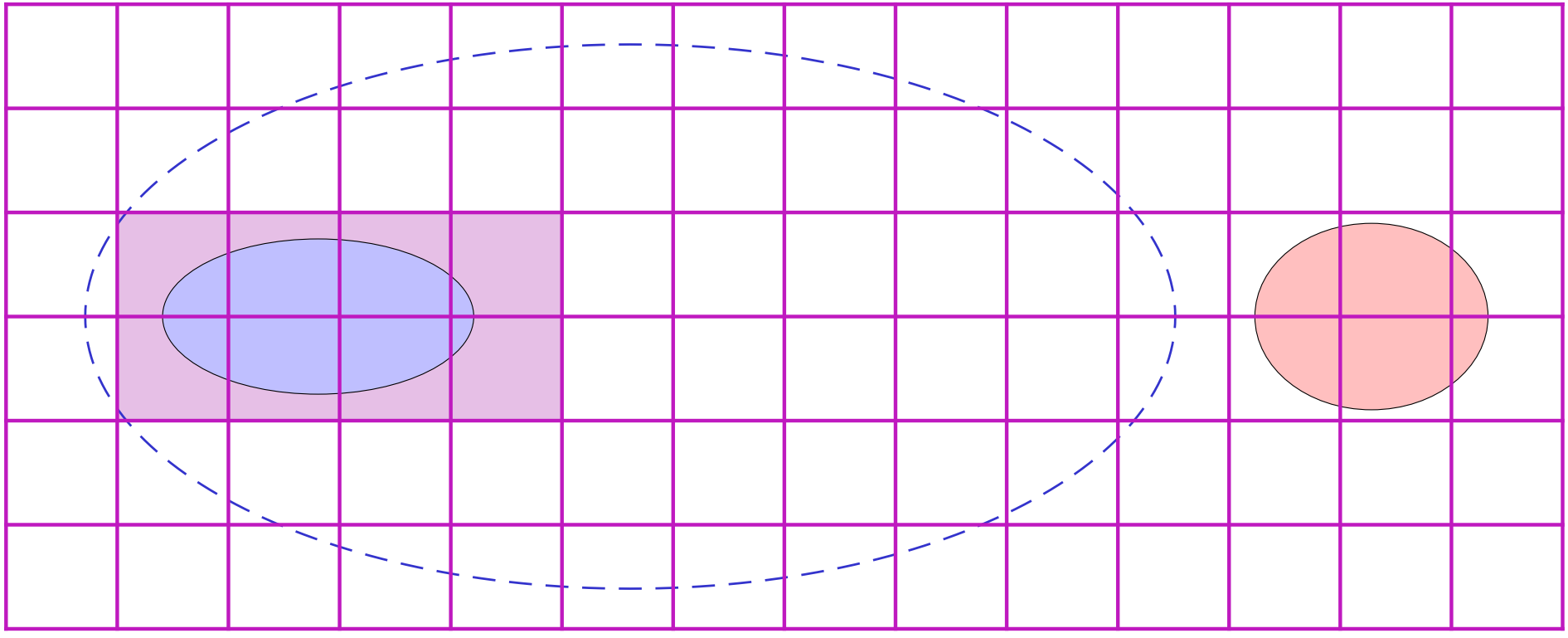

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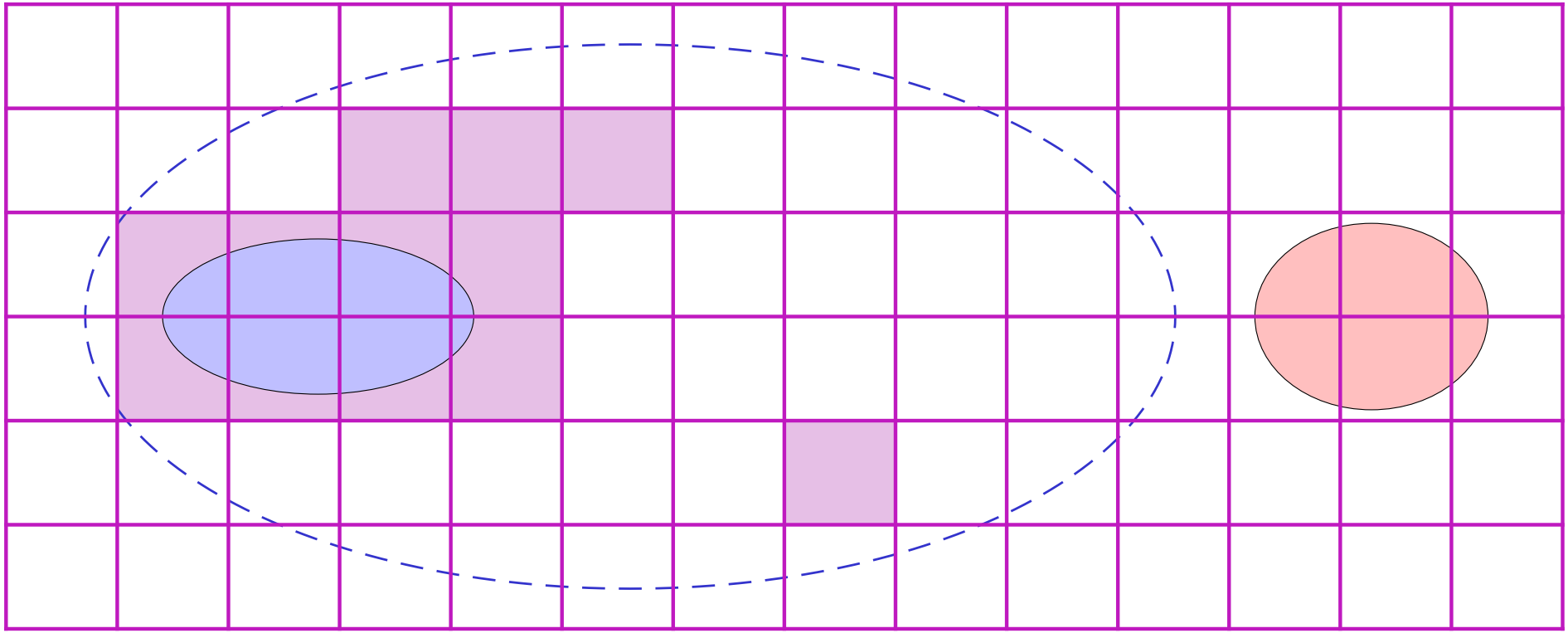

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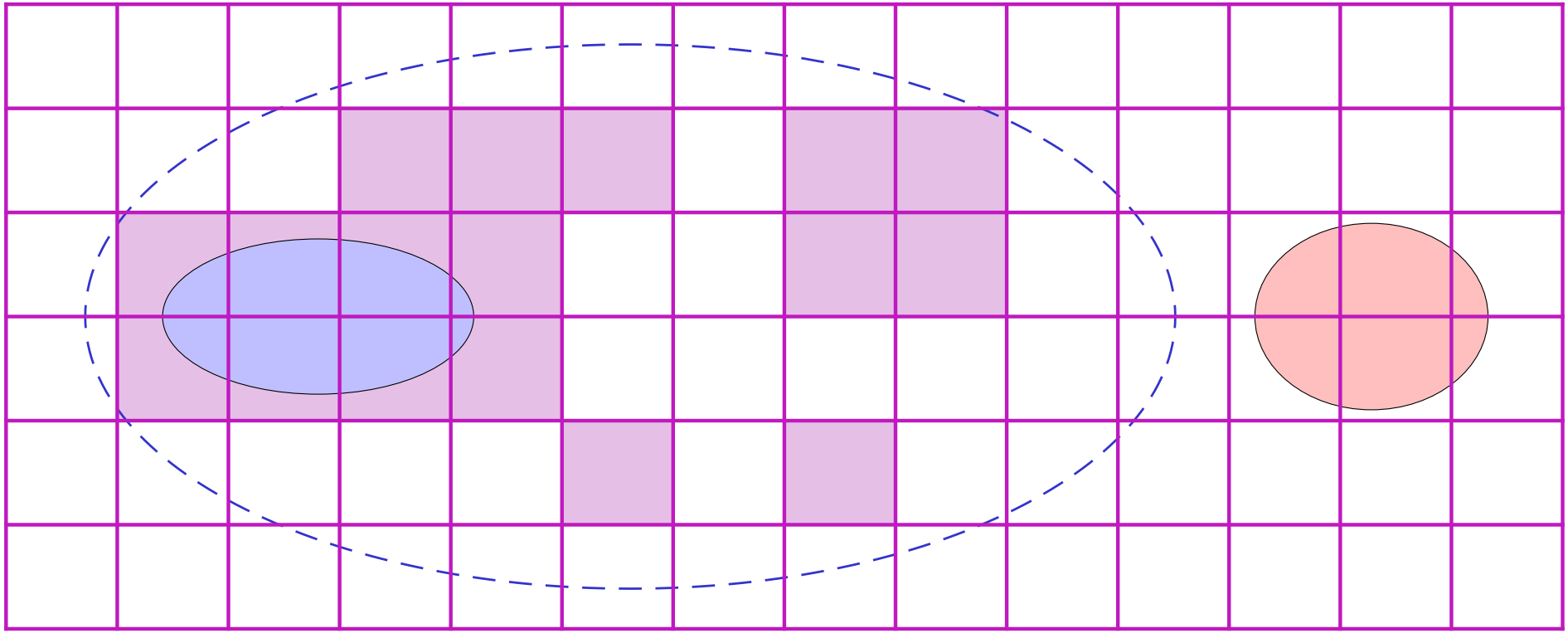

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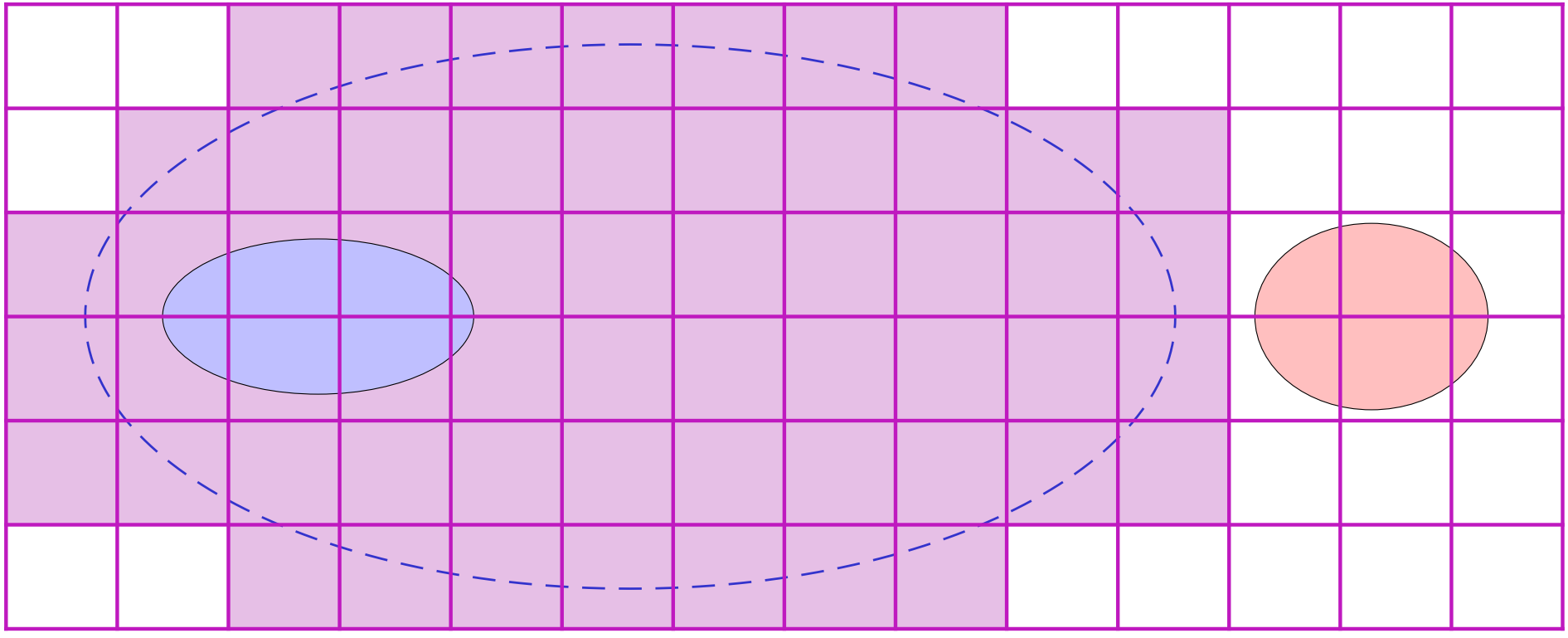

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- The refined abstraction is safe!

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- Previous work: batch-oriented abstract-check-refine loop
  - Clarke et al.: ACTL^* but for finite-state systems [CGJ+00]
  - MSR SLAM Project safety properties for systems code [BR01]

Abstract-Check-Refine Loop (cont'd)

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4. refinement
   - extract an "explanation" of unfeasibility of π as new predicates $P'_1, P'_2, \ldots, P'_k$
   - $\mathcal{P} := \mathcal{P} \cup \{P'_1, P'_2, \ldots, P'_k\}$
5. **goto** 1.

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→ Need a lazy approach

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→ Give control to the model-checker

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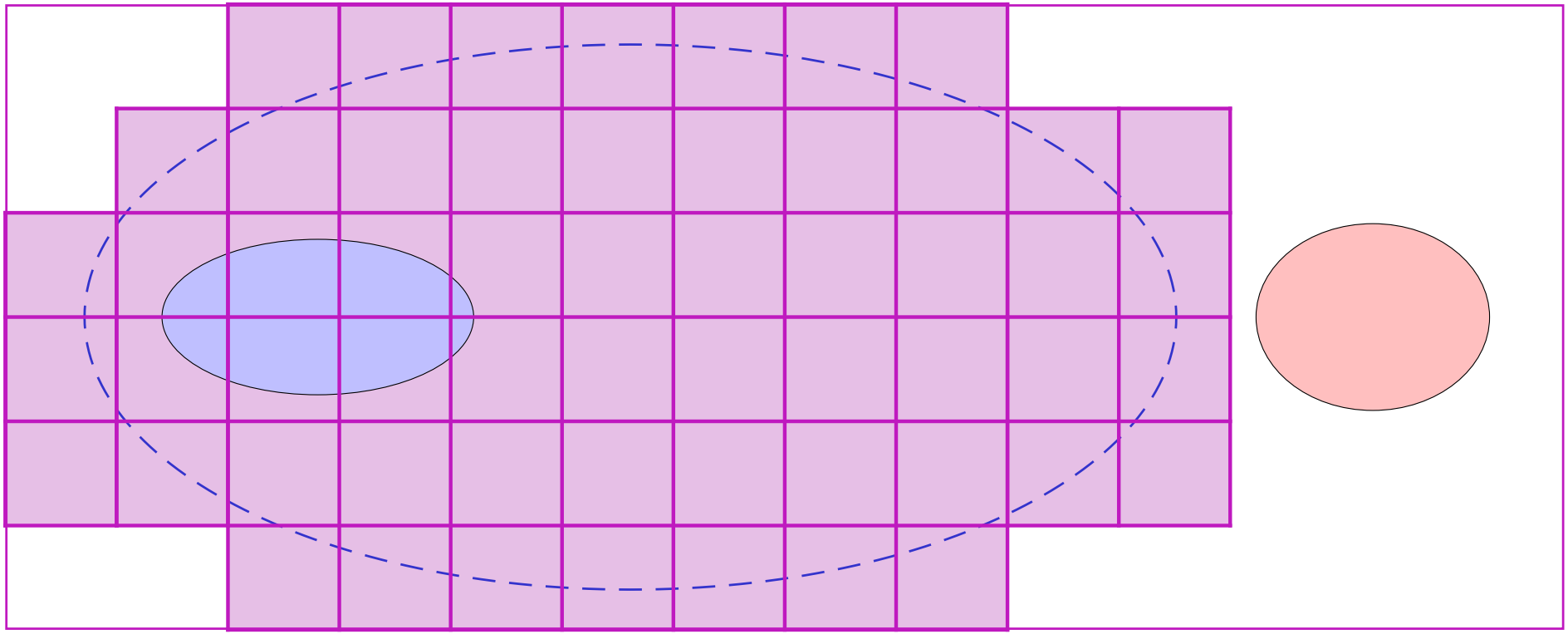

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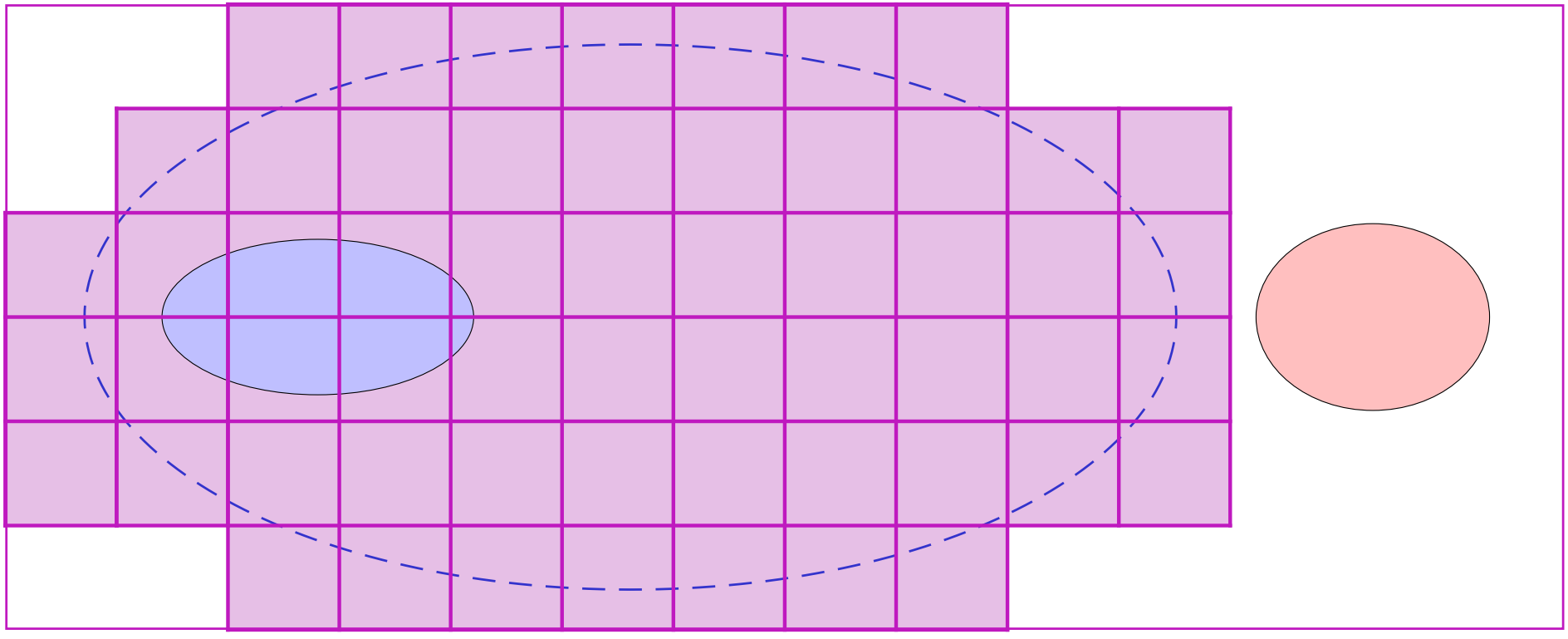

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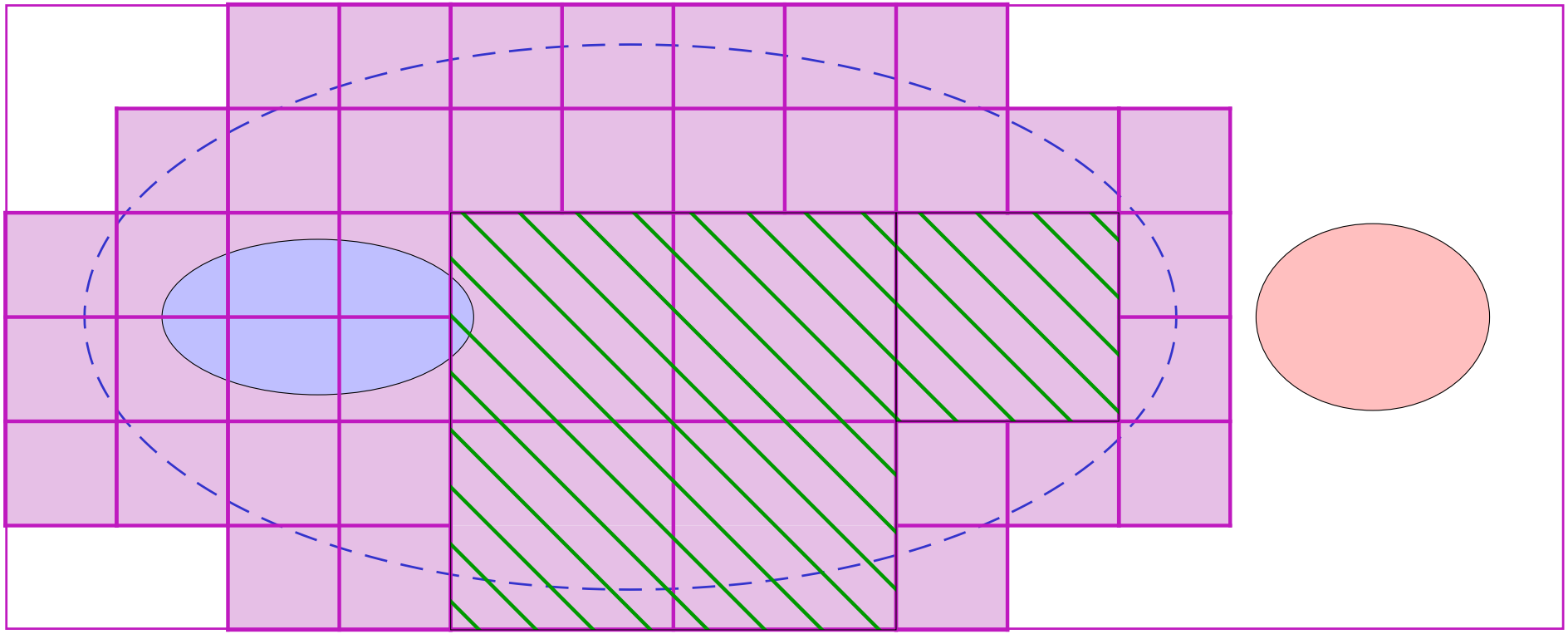

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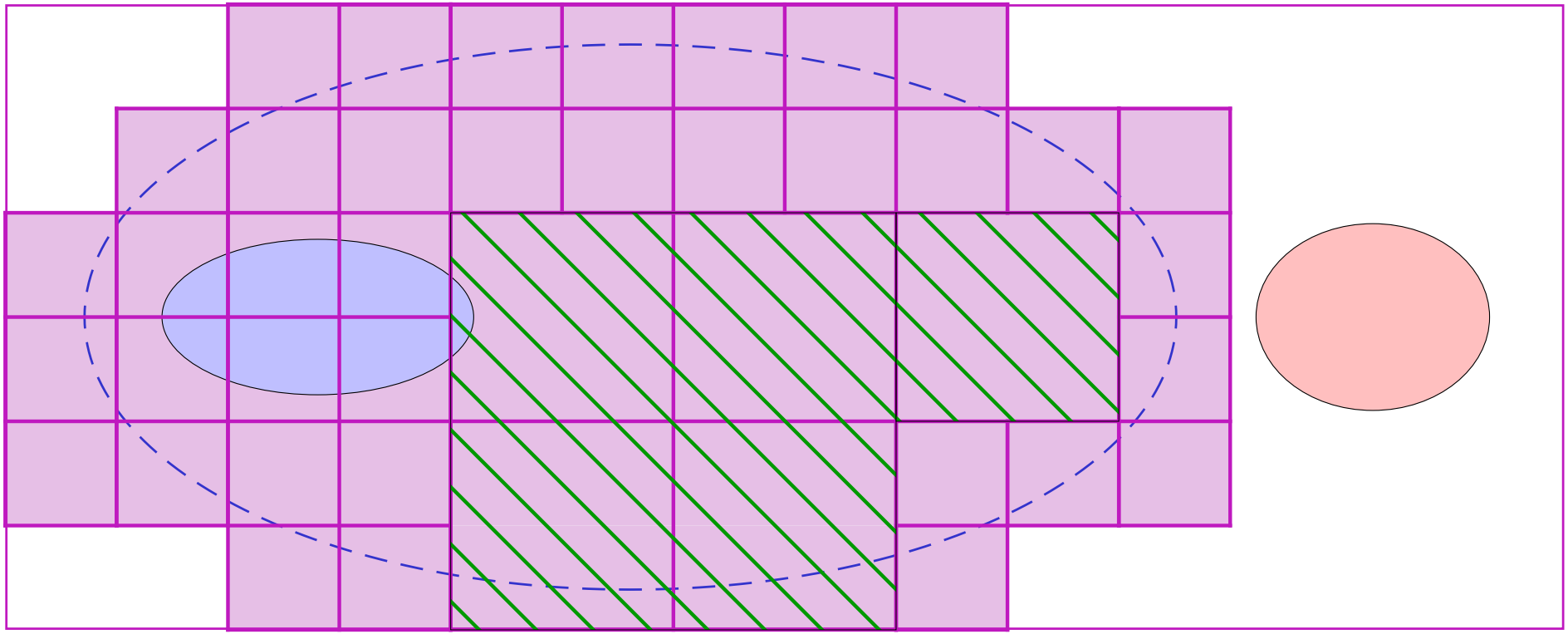

- Why be precise everywhere?
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- Local refinement: driven by the search

Abstraction Structure

- Labelled Transition System: $(S, \Sigma, \rightarrow)$
- Abstraction structure: $(R, \bot, \sqcup, \sqcap, pre, \widehat{post}, [\![\cdot]\!], \trianglelefteq)$

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Abstraction Structure

- Labelled Transition System: $(S, \Sigma, \rightarrow)$
- Abstraction structure: $(R, \bot, \sqcup, \sqcap, pre, \widehat{post}, [\![\cdot]\!], \trianglelefteq)$
- set R of regions, meaning given by $[\![\cdot]\!] : R \rightarrow S$
- induced inclusion pre-order $\sqsubseteq$ over regions: $r \sqsubseteq r'$ iff $[\![r]\!] \subseteq [\![r']\!]$
- empty region $\bot$ ($[\![\bot]\!] = \emptyset$)
- union and intersection of regions: $[\![r \sqcup r']\!] = [\![r]\!] \cup [\![r']\!]$, $[\![r \sqcap r']\!] = [\![r]\!] \cap [\![r']\!]$
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- abstract $\widehat{post}$: $[\![\widehat{post}(r, l)]\!] \supseteq \{s' \in S \mid \exists\, s \in [\![r]\!].\, s \xrightarrow{l} s'\}$
- precision pre-order $\trianglelefteq$ over regions: $\widehat{post}$ monotonic w.r.t. $\trianglelefteq \cap \sqsubseteq$
  - usually, $\widehat{post}$ is neither monotonic w.r.t. $\trianglelefteq$, nor monotonic w.r.t. $\sqsubseteq$

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- precision pre-order is containment on support predicates

Lazy Symbolic Reachability Tree

create root $\mathtt{r}$ labeled with r_0

while there are unmarked nodes

pick an unmarked node $\mathtt{n}:r$

if $r \sqcap err \not\equiv \bot$

let $\mathtt{n}':r' \xrightarrow{\sigma} \mathtt{n}:r$ be the oldest ancestor of $\mathtt{n}$ with $pre(err,\sigma) \sqcap r' \not\equiv \bot$

if $\mathtt{n}'$ is the root **then return** the "error trace" σ

else `do_refinement()`

else if $r \sqsubseteq \bigsqcup \{u \mid \mathtt{m}:u \text{ is an uncovered marked node}\}$

mark $\mathtt{n}$ as *covered*

else for each label $l \in \Sigma$ **do**

$r' \leftarrow \widehat{post}(r,l)$

construct a son $\mathtt{n}':r'$ of $\mathtt{n}$ and label the arc $\mathtt{n} \xrightarrow{l} \mathtt{n}'$

mark $\mathtt{n}$ as *uncovered*

return the region $\bigsqcup \{u \mid \mathtt{m}:u \text{ is an uncovered marked node}\}$

Lazy Refinement

When entering `do_refinement()`, we have:

- $\mathtt{n}' : r' \xrightarrow{\sigma} \mathtt{n} : r$ is the oldest ancestor of `n` with $pre(err, \sigma) \sqcap r' \not\equiv \bot$
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So we have: $\mathtt{n}'' : r'' \xrightarrow{l} \mathtt{n}' : r' \xrightarrow{\sigma} \mathtt{n} : r$ and $pre(err, l\sigma) \sqcap r'' \equiv \bot$

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→ The rest of the tree also needs to be updated...

Lazy Refinement (cont'd)

Updating:

- either the subtree starting at the sons of the refined node $\mathtt{n}''$ are removed
- or only regions along the path $\mathtt{n}'' : w'' \xrightarrow{l} \mathtt{n}' : r' \xrightarrow{\sigma} \mathtt{n} : r$ are re-computed

Unmarking recent leaves to garantee correctness:

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Theorem When the lazy abstraction algorithm terminates, either:

- it returns an error-free over-approximation of the (concrete) reachability set, or
- it returns a concrete error path.

Application to predicate abstraction

We re-label $\mathtt{n}'' : r''$ by w'' satisfying $w'' \equiv r''$, $w'' \trianglelefteq r''$ and $\widehat{post}(w'', l\sigma) \equiv \bot$

- Refining a region consists in adding more support predicates
- New support predicates should rule out the spurious error trace

  $\rightarrow$ Predicate discovery

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- General setting
  - Application to other classes of systems (e.g. hybrid systems)

Lazy predicate abstraction of C

- Control Flow Automata
  - $\Sigma = \mathtt{Op}$: blocks of assignments, if conditions, function calls
  - safety-monitor automaton
- Predicate language $\mathcal{L}$: theory of equality with uninterpreted functions + integer arithmetic

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- Control locations kept explicit: nodes labeled with (q, r)
- Predicate discovery (from a false error trace):
  - Keep substitutions explicit
    - introduce new (existentially quantified) variables
    - all operations appear explicitly
  - Ask a proof of unsatisfiability
  - Pick predicates appearing in the proof

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2. Predicate Abstraction
3. Lazy Abstraction
4. **Proof Generation**
5. Experiments
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Proof Carrying Code [Nec97]

- Verification Condition (VC)
  - first-order formula whose validity ensures correctness of the program
  - automatically computed from the annotated program code
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- Proof checking is much easier than verification!

Temporal Safety Certification

- Assumption: the program code is a CFA
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    - but can use safety monitors to express safety properties
- Applying PCC
  - compute the invariant annotations
  - compute the VC
  - Generate the proof

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$$VC \quad = \quad Inv(q_0) \quad \wedge \quad \neg Inv(err) \quad \wedge \quad \bigwedge_{q \xrightarrow{\texttt{op}} q'} \left(sp(Inv(q), \texttt{op}) \implies Inv(q') \right)$$

Invariant Generation via Lazy Abstraction

Assume that the lazy abstraction reachability tree, from $(q_0, \texttt{true})$, is computed with no error found. Then:

- for each node $\texttt{n} : (\mathit{err}, r)$ in the tree, r is empty
- if $\texttt{n} : (q, r) \xrightarrow{\texttt{op}} \texttt{n}' : (q', r')$ then $sp(r, \texttt{op}) \implies r'$
- if $\texttt{n} : (q, r)$ is a covered leaf, then there are internal nodes $\texttt{n}_1 : (q, r_1)$, $\texttt{n}_2 : (q, r_2), \ldots, \texttt{n}_k : (q, r_k)$ such that $r \implies r_1 \vee r_2 \vee \cdots \vee r_k$

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Take:

$$Inv(q) \quad = \quad \bigvee_{\texttt{n}:(q,r)} \quad r$$

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- The other case is similar

Proof Generation (cont'd)

Optimized in two ways:

- simple proofs of $sp(Inv(q), \texttt{op}) \implies Inv(q')$, where parts of the disjuncts are matched using the tree
- non-uniform predicate abstraction results in fewer proof obligations

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The BLAST tool

- Berkeley Lazy Abstraction Software Verification Tool

```
http://www-cad.eecs.berkeley.edu/~tah/blast/
```

- Applies lazy abstraction and proof generation to C programs
  - handles all syntactic constructs of C (MSVC and GCC extensions)
  - applied to Linux and Windows NT device drivers
- 10K lines of Objective Caml

The BLAST tool (cont'd)

BLAST uses:

- CIL compiler infrastructure [NMRW02]
  - to parse C programs and produce Control FLow Automata
- CUDD package [Som98]
  - to represent regions as BDDs over support predicates
- Simplify theorem prover [DNS]
  - for abstract post computation and inclusion check
- Vampyre proof generating theorem [Vam]
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BLAST is modular:

- lazy abstraction algorithm implemented by an OCaml functor
- can use different abstraction structures

Checking drivers with BLAST

- Linux device drivers
  - checked locking discipline
  - safety-monitor automaton with 3 states
  - found interprocedural bugs in the locking behavior
- Windows NT device drivers (from the Windows NT DDK)
  - I/O Request Packet Completion Specification
    - sequence of functions to be called
    - specific return codes
  - safety-monitor automaton with 22 states
  - found bugs involving incorrect status codes

Checking drivers with BLAST (cont'd)

Program	Post-processed LOC	Predicates		BLAST Time (sec)	Proof Size (bytes)
		Total	Active		
`qpmouse.c`	23539	2	2	0.50	175
`ide.c`	18131	5	5	4.59	253
`aha152x.c`	17736	2	2	20.93	
`tlan.c`	16506	5	4	428.63	405
`cdaudio.c`	17798	85	45	1398.62	156787
`floppy.c`	17386	62	37	2086.35	
[fixed]		93	44	395.97	60129
`kbfiltr.c`	12131	54	40	64.16	
[fixed]		37	34	10.00	7619
`mouclass.c`	17372	57	46	54.46	
`parport.c`	61781	193	50	1980.09	102967

- On a 700 MHz Pentium III with 256 MB RAM

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Conclusion

Lazy abstraction:

- optimizes the three phases of the abstract-check-refine loop
  - model-checking driven
  - local refinement
- enables the automatic construction of small proof certificates
  - proof is generated from the error-free symbolic reachability tree
- has been implemented in the tool BLAST
  - ability to analyze real device drivers (60K lines of C)
  - generates small proofs (less than 150Kb)

Problems & Future Work

- Recursion
  - BLAST currently uses an explicit (unbounded finite) stack
- Acceleration of loops
- Application to other classes of systems (hybrid systems, protocols, ...)
- Efficient operations on interpreted BDDs
- Completeness results
- Non predicate based abstraction structures
  - add abstraction and refinement in symbolic model-checkers?

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