

Learning weighted and probabilistic automata

Alexandra Silva



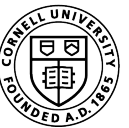
Active learning

Infer automaton through oracle (membership and equivalence queries)

Deterministic
finite automata

Gold, Angluin 80's

Weighted
automata



Active learning

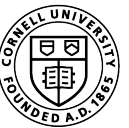
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$$L \in 2^{A^*}$$



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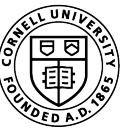
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Weighted
automata

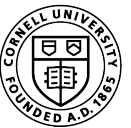
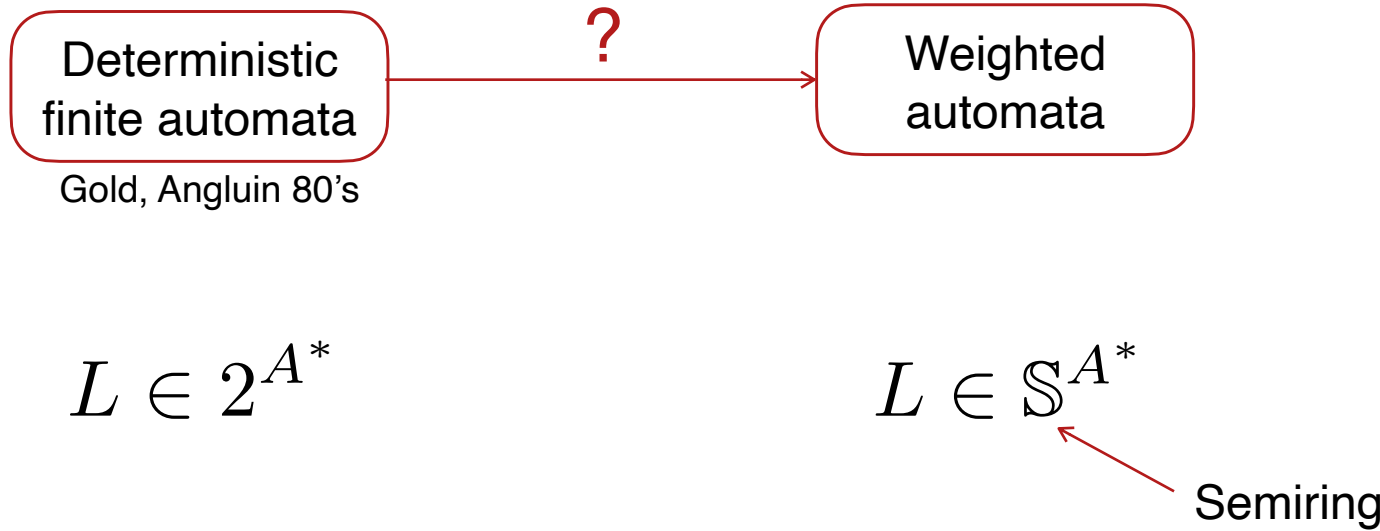
$$L \in \mathbb{S}^{A^*}$$

← Semiring



Active learning

Infer automaton through oracle (membership and equivalence queries)



L^* for DFAs

L^* learns minimal DFA for a *regular language* assuming an oracle that answers:

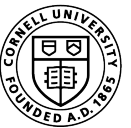


L^* for DFAs

L^* learns minimal DFA for a *regular language* assuming an oracle that answers:

Membership queries

$$w \in \mathcal{L}?$$



L^* for DFAs

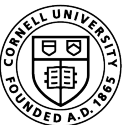
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$$\mathcal{L}(H) = \mathcal{L}?$$



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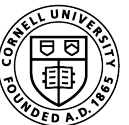
Membership queries

$$w \in \mathcal{L}?$$

Equivalence queries

$$\mathcal{L}(H) = \mathcal{L}?$$

↖ No = counter-example



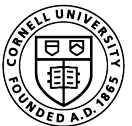
L^* for DFAs

$$S, E \subseteq A^*$$

		E	
		ε	a
S	ε	1	0
	a	0	1
	aa	1	0
$S \cdot A$	aaa	0	1

$\mathcal{L} = \{a^n \mid n \text{ is even}\}$

$aa \cdot a \notin \mathcal{L}$



L* for DFAs

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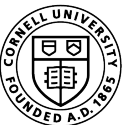
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$$S, E \leftarrow \{\varepsilon\}$$

Repeat until no more counterexamples:

1. Close table (changing S)
2. Equivalence query
3. Add suffixes of counterexample to E



L^* for DFAs, example

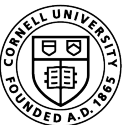
$$A = \{a\}$$

$$a^n \in \mathcal{L} \iff n \equiv 0 \pmod{3}$$

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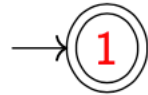


L^* for DFAs, example

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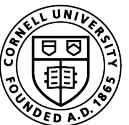
	ε
ε	1
a	0



→ $S, E \leftarrow \{\varepsilon\}$

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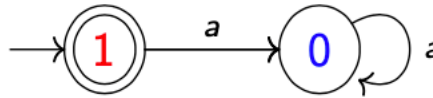


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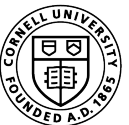
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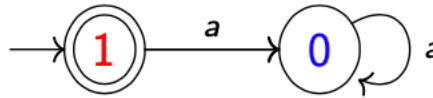


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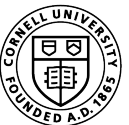


Counterexample: aaa

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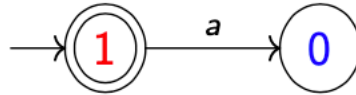


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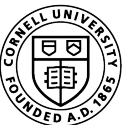


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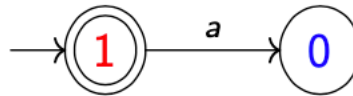


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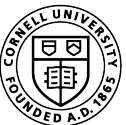


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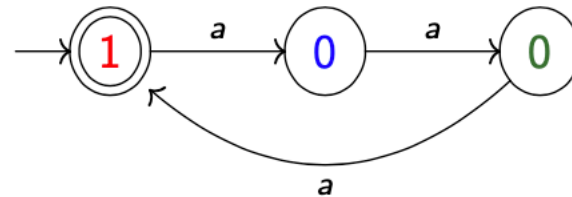


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	ϵ	a	aa	aaa
ϵ	1	0	0	1
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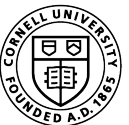


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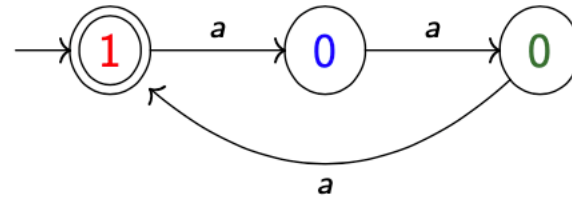


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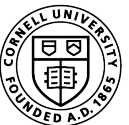
	ε	a	aa	aaa
ε	1	0	0	1
a	0	0	1	0
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$$S, E \leftarrow \{\varepsilon\}$$

Repeat until no more counterexamples:

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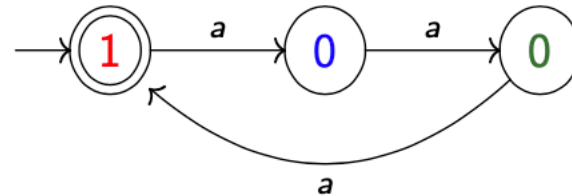


L* for DFAs, example

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	ε	a	aa	aaa
ε	1	0	0	1
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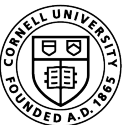


Terminates!

$$S, E \leftarrow \{\varepsilon\}$$

➔ **Repeat until no more counterexamples:**

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DFAs vs WFAs

$\mathbb{S}$ semiring (e.g. $\mathbb{R}, \mathbb{Q}, \mathbb{Z}, \mathbb{N}, 2$), FQ free semimodule over Q

DFA

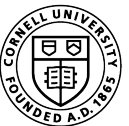
initial state in Q

$$\begin{array}{c} Q \\ \downarrow \\ 2 \times Q^A \end{array}$$

WFA

initial state in FQ

$$\begin{array}{c} Q \\ \downarrow \\ \mathbb{S} \times (FQ)^A \end{array}$$



DFAs vs WFAs

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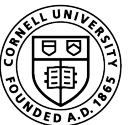
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WFA

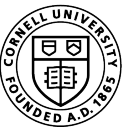
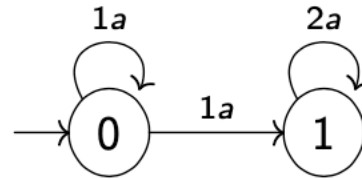
initial state in FQ

$$\begin{array}{c} Q \\ \downarrow \\ \mathbb{S} \times (FQ)^A \end{array}$$

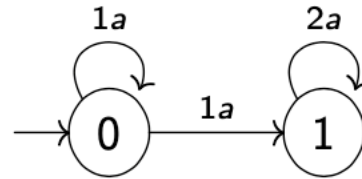
Accepts weighted language $A^* \rightarrow \mathbb{S}$
Multiplies along the path with final output
Sums over paths



DFAs vs WFAs



DFAs vs WFAs

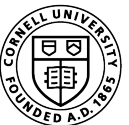


$$\mathcal{L}(\varepsilon) = 0$$

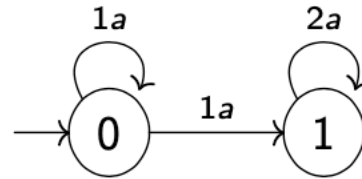
$$\mathcal{L}(a) = 1 \cdot 0 + 1 \cdot 1 = 1$$

$$\mathcal{L}(aa) = 1 \cdot 1 \cdot 0 + 1 \cdot 1 \cdot 1 + 1 \cdot 2 \cdot 1 = 3$$

$$\mathcal{L}(aaa) = 1 \cdot 1 \cdot 1 \cdot 0 + 1 \cdot 1 \cdot 1 \cdot 1 + 1 \cdot 1 \cdot 2 \cdot 1 + 1 \cdot 2 \cdot 2 \cdot 1 = 7$$



DFAs vs WFAs



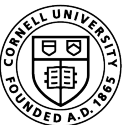
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$$\mathcal{L}(a^n) = 2^n - 1$$



Learning WFAs

Table:

Cells have values from semiring rather than 0,1

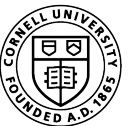
Membership Queries:

Return weight associated with word

Equivalence Queries:

Submit hypothesis WFA

Counterexample = work on which weight differs

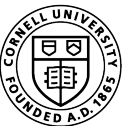


Learning WFAs

$S, E \leftarrow \{\varepsilon\}$

Repeat until no more counterexamples:

1. Close table (changing S)
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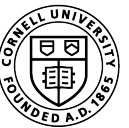
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each lower row a linear combination of upper rows



Learning WFAs

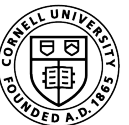
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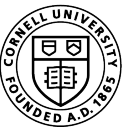
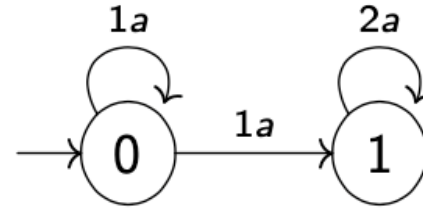
each lower row a linear combination of upper rows

Requirement for semiring: solving linear systems of equations should be computable.



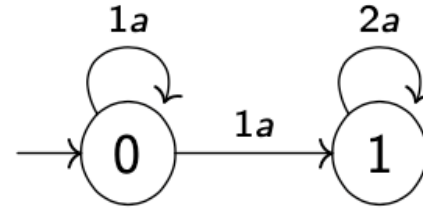
Learning WFAs, example

$$\mathcal{L}(a^n) = 2^n - 1$$

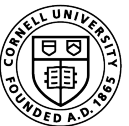
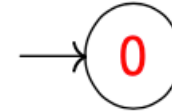


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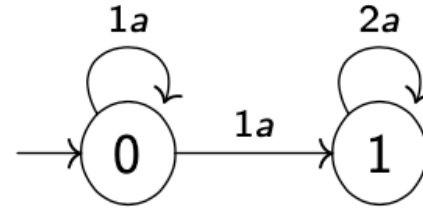


	ε
ε	0
a	1

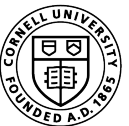
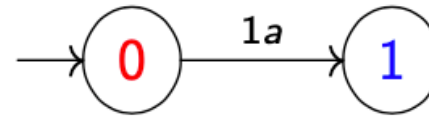


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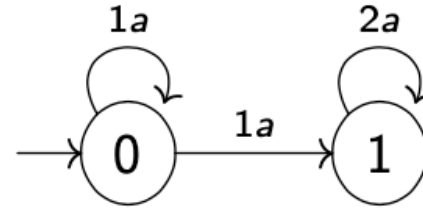


	ε
ε	0
a	1
aa	3

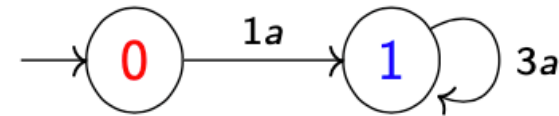


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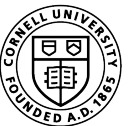
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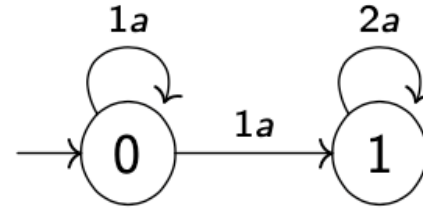


Counterexample: aaa

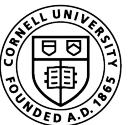
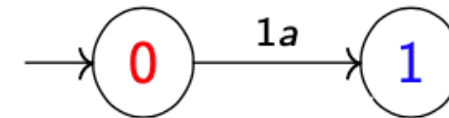


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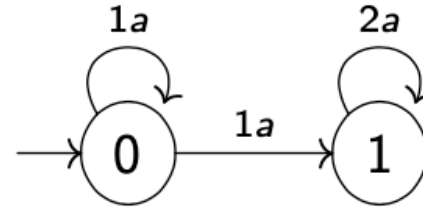


	ϵ	a	aa	aaa
ϵ	0	1	3	7
a	1	3	7	15
aa	3	7	15	31

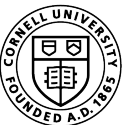
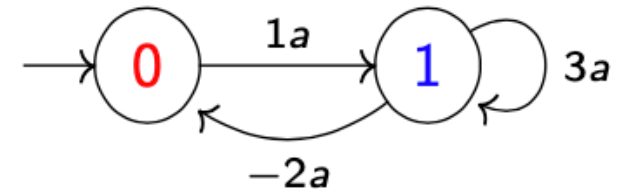


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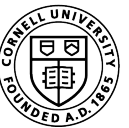
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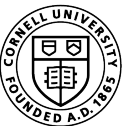


Does it terminate?



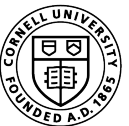
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L* for DFAs: termination consequence of regular languages having finitely many Myhill-Nerode classes = minimal DFA



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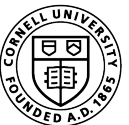
L* for DFAs: termination consequence of regular languages having finitely many Myhill-Nerode classes = minimal DFA



Does it terminate?

L* for DFAs: termination consequence of regular languages having finitely many Myhill-Nerode classes = minimal DFA

L* for WFAs: depends on the semiring

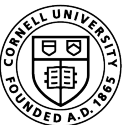


Does it terminate?

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***Field:** terminates as a consequence of basis existence, our algorithm instantiates one of Bergadano and Varricchio (1996)*



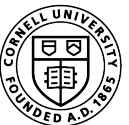
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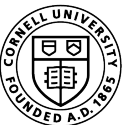
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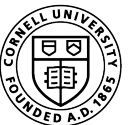
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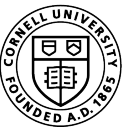
NFAs have no minimal representative!



Learning WFAs

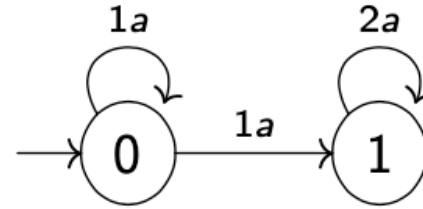
Does it terminate for any semiring?

No.

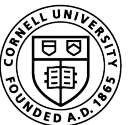


The bad semiring

$$\mathcal{L}(a^n) = 2^n - 1$$

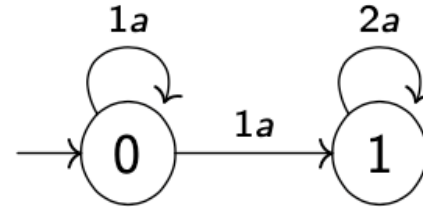


Learning over $\mathbb{Q}$

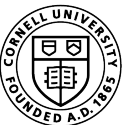
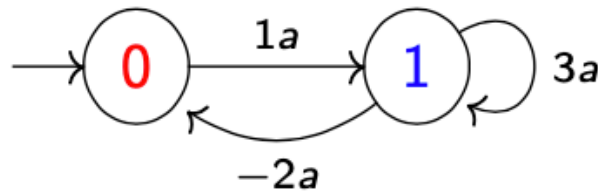


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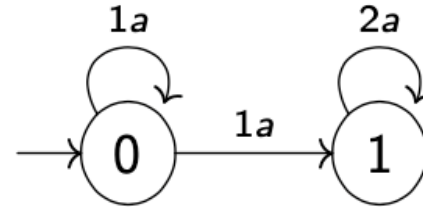


Learning over $\mathbb{Q}$

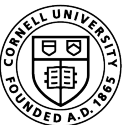
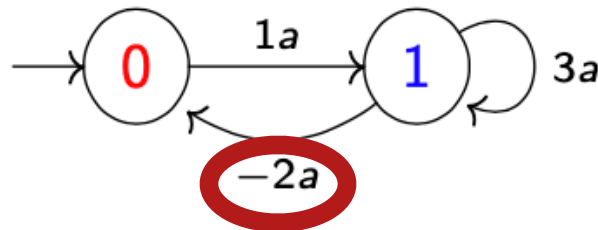


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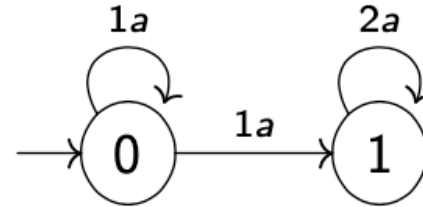


Learning over $\mathbb{Q}$

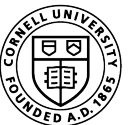
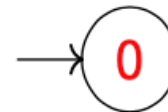


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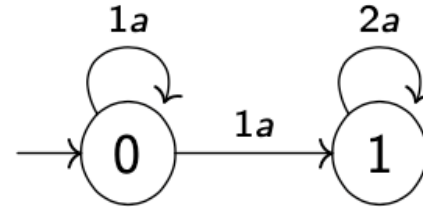


	ε	a
ε	0	1
a	1	3

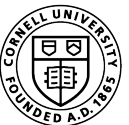
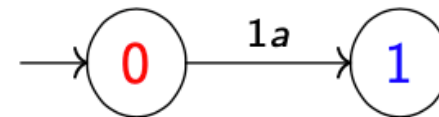


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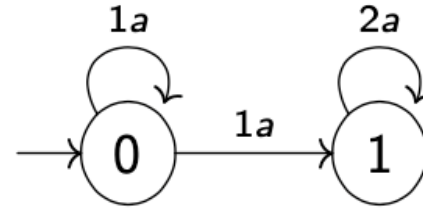


	ε	a
ε	0	1
a	1	3
aa	3	7

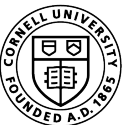
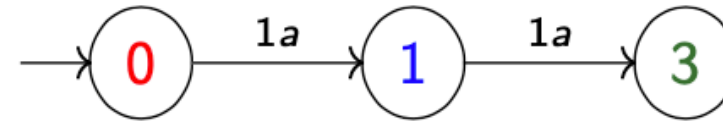


The bad semiring

$$\mathcal{L}(a^n) = 2^n - 1$$

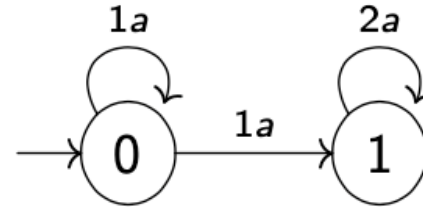


	ϵ	a
ϵ	0	1
a	1	3
aa	3	7
aaa	7	15

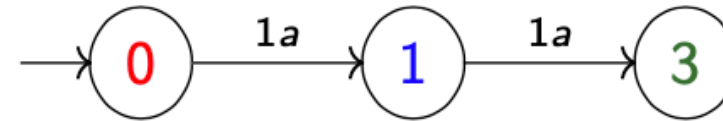


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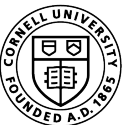
$$\mathcal{L}(a^n) = 2^n - 1$$



	ε	a
ε	0	1
a	1	3
aa	3	7
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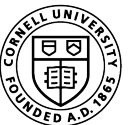
...



Termination issue

The algorithm approximates the **Hankel matrix** of the language. Linear combinations of rows in:

	ϵ	a	aa	aaa	$\dots$
ϵ	0	1	3	7	
a	1	3	7	15	
aa	3	7	15	31	$\dots$
aaa	7	15	31	63	
$\dots$			$\dots$		

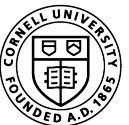


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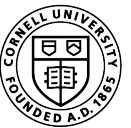
	ϵ	a	aa	aaa	$\dots$
ϵ	0	1	3	7	
a	1	3	7	15	
aa	3	7	15	31	$\dots$
aaa	7	15	31	63	
$\dots$			$\dots$		

This is not finitely generated (over commutative monoids)



Termination Conditions

Algorithm terminates assuming:



Termination Conditions

Algorithm terminates assuming:

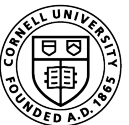
Progress measure with bound

number, increases when rows separate via extra column

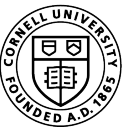
Ascending chain condition on Hankel matrix

Subsemimodule chains converge: if $S_1 \subseteq S_2 \subseteq \dots \subseteq H$ are subsemimodules, then $\exists n :$

$$S_n = S_{n+1} = S_{n+2} = \dots$$



Termination Argument

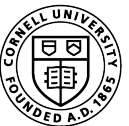


Termination Argument

Assume:

Progress measure with bound

Ascending chain condition on Hankel Matrix



Termination Argument

Assume:

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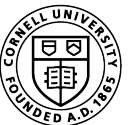
Then:

Modules generated by (S_n, A^*) form chain below Hankel matrix

Converges, from that point on closedness guaranteed

Bounded progress measure $\Rightarrow$ finitely many counterexamples

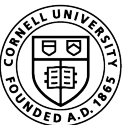
Counter example always leads to closedness defect or rows distinguished by new column



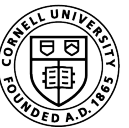
Summary

Main ingredients for effective terminating algorithm:

1. Progress measure with bound
2. Ascending chain condition on Hankel matrix
3. Procedure to determine/fix closedness: solvability of finite system of linear equations



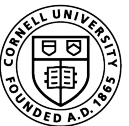
Learning over a field



Learning over a field

1. Progress measure with bound

- Dimension of vector space spanned by table
- $\leq$ minimal WFA size



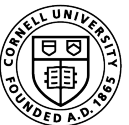
Learning over a field

1. Progress measure with bound

- Dimension of vector space spanned by table
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2. Ascending chain condition on Hankel matrix

- Vector space dimension increases with strict inclusion
- Minimal WFA size = Hankel matrix dimension



Learning over a field

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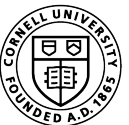
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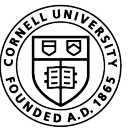
- Vector space dimension increases with strict inclusion
- Minimal WFA size = Hankel matrix dimension

3. Procedure for closedness: solvability of finite system of linear equations

- Gaussian elimination



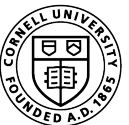
Learning over a finite semiring



Learning over a finite semiring

1. Progress measure with bound

- Set size of semimodule spanned by table
- $\leq$ determinization of correct automaton



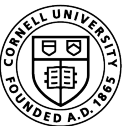
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Learning over a finite semiring

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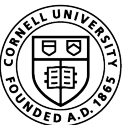
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3. Procedure for closedness: solvability of finite system of linear equations

- Try all linear combinations of rows



Learning over a finite semiring

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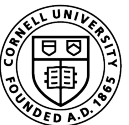
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Fields and finite semirings OK, can we do more?



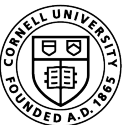
Principal ideal domains

Principal ideal domain = *integral domain* with *all ideals principal*

Integral domain: commutative ring, $ab=0 \Rightarrow a=0 \vee b=0$

All ideals principal: generated by one element

Examples: $\mathbb{Z}$, $\mathbb{Z}[i]$, $K[x]$ for K a field



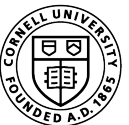
Modules over PID

A module is free if and only if it is torsion free: $pm=0 \Rightarrow p=0 \vee m=0$

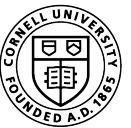
A submodule of a free and finitely generated module is

- Free and **finitely** generated
- With **smaller** (or equal) rank

If a finitely generated free module is a quotient of another, its rank is smaller or equal



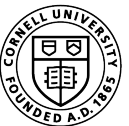
Learning over PIDs



Learning over PIDs

1. Progress measure with bound

- Rank of the module spanned by the table (which is free and f.g!)
- $\leq$ rank of Hankel matrix



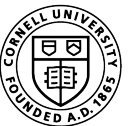
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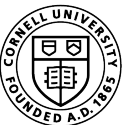
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3. Procedure for closedness: solvability of finite system of linear equations

- Solve equations via Smith normal form (exists for PIDs), some further assumptions on computability (hold for integers)



Learning over PIDs

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- Rank of the module spanned by the table (which is free and f.g!)
- $\leq$ rank of Hankel matrix

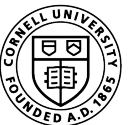
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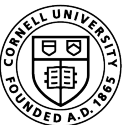
Learning algorithm terminates for the integers!



Key takeaway

Active learning algorithm for WFAs:

1. Termination depends on properties of the semiring: works for fields, finite semirings, integers, not naturals.
2. Solvability of finite systems of linear equations essential.



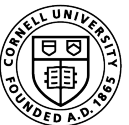
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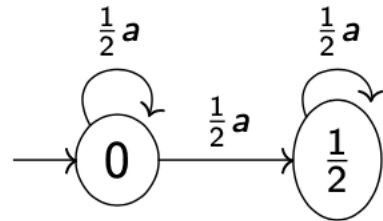
1. Termination depends on properties of the semiring: works for fields, finite semirings, integers, not naturals.
2. Solvability of finite systems of linear equations essential.

How about probabilistic automata?

$$A^* \rightarrow [0, 1]$$

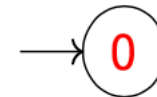


Probabilistic automata

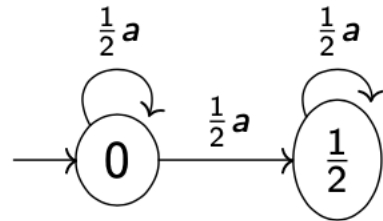


$$\mathcal{L}(a^n) = \frac{n}{2^{n+1}}$$

	ε
ε	0
a	0.25

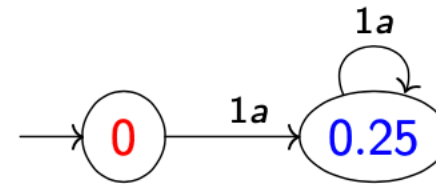


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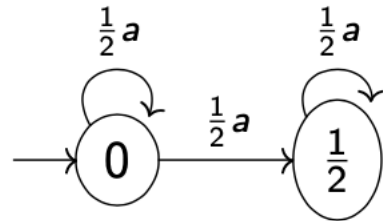


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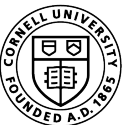


Probabilistic automata

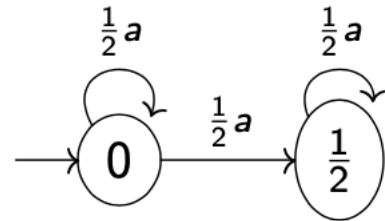


$$\mathcal{L}(a^n) = \frac{n}{2^{n+1}}$$

	ϵ	a
ϵ	0	0.25
a	0.25	0.25
aa	0.25	0.1875

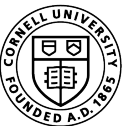


Probabilistic automata

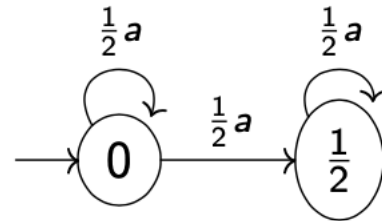


$$\mathcal{L}(a^n) = \frac{n}{2^{n+1}}$$

	ε	a
ε	0	0.25
a	0.25	0.25
aa	0.25	0.1875
aaa	0.1875	0.125

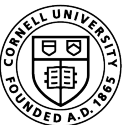


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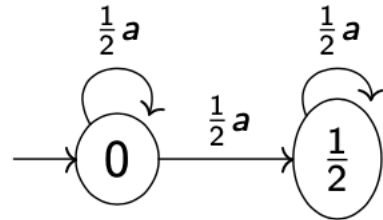


$$\mathcal{L}(a^n) = \frac{n}{2^{n+1}}$$

	ε	a	Ratio
ε	0	0.25	0
a	0.25	0.25	1
aa	0.25	0.1875	1.333...
aaa	0.1875	0.125	1.5



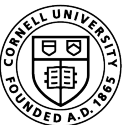
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	ϵ	a	Ratio
ϵ	0	0.25	0
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aa	0.25	0.1875	1.333...
aaa	0.1875	0.125	1.5

Problem: rows of the table are not finitely generated

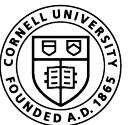


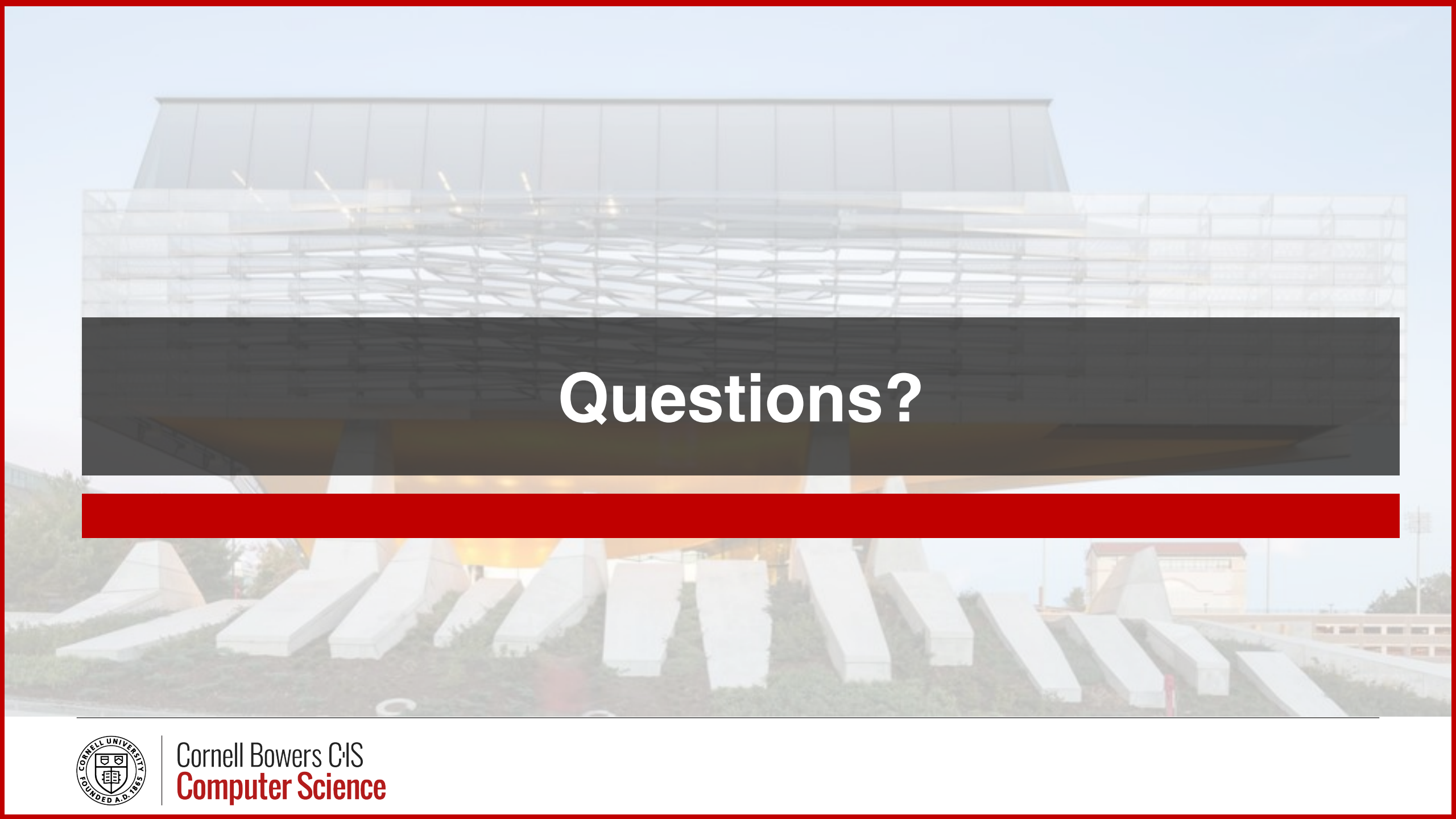
Probabilistic automata, partial solutions

Ongoing work with Leon Witzman

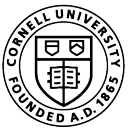
- If we know the number of states of target automaton, there exists an active learning algorithm (that uses at most exponential space);
- Even if the real automaton has rational coefficients the systems we solve might lack rational solutions (real algebraic numbers);
- Use a quadratic program to approximate solution;
- Counterexample handling (to avoid assuming number of states) unclear;
- Learning happens in convex sets, can we use this algebraic structure?

???



A photograph of the Bowers Hall at Cornell University, featuring a modern glass and steel upper section and a lower section with large, angled concrete pillars. A semi-transparent black banner is overlaid across the middle of the image.

Questions?



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Computer Science