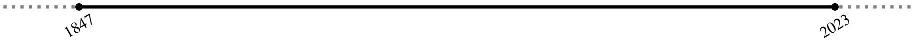
Thinking with Circuits

From Logic to Probabilistic and Back

Renato Lui Geh

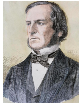
Circuits?



Circuits?

Circuits?

George Boole



1847 — 2023

Boolean Algebra

Propositional logic?

$$x, y \in \{0, 1\}$$

$x \wedge y \Leftrightarrow$

x	y	$x \wedge y$
0	0	0
0	1	0
1	0	0
1	1	1

$x \vee y \Leftrightarrow$

x	y	$x \vee y$
0	0	0
0	1	1
1	0	1
1	1	1

$\neg x \Leftrightarrow$

x	$\neg x$
0	1
1	0

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

Satisfiability and Model Counting

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Are there $X = x$, $Y = y$, $Z = z$ s.t.

$$\phi(X = x, Y = y, Z = z) = 1?$$

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

Are there $X = x, \quad Y = y, \quad Z = z \quad$ s.t.

$$\phi(X = x, Y = y, Z = z) = 1?$$

x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1	1	0	0	1
0	0	1	0	1	0	1	1
0	1	0	1	1	1	0	0
0	1	1	1	1	1	1	1

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

Are there $X = x$, $Y = y$, $Z = z$ s.t.

$$\phi(X = x, Y = y, Z = z) = 1?$$

x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1 ✓	1	0	0	1 ✓
0	0	1	0 ✗	1	0	1	1 ✓
0	1	0	1 ✓	1	1	0	0 ✗
0	1	1	1 ✓	1	1	1	1 ✓

SAT = ✓

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \land (\neg Y \lor Z)] \lor [(\neg Z \lor Y) \land \neg X]$$

Are there $X = x$, $Y = y$, $Z = z$ s.t.

$$\phi(X = x, Y = y, Z = z) = 1?$$

x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1 ✓	1	0	0	1 ✓
0	0	1	0 ✗	1	0	1	1 ✓
0	1	0	1 ✓	1	1	0	0 ✗
0	1	1	1 ✓	1	1	1	1 ✓

SAT = ✓

NP-complete

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

How *many* $X = x$, $Y = y$, $Z = z$ s.t.

$$\phi(X = x, Y = y, Z = z) = 1?$$

x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1	1	0	0	1
0	0	1	0	1	0	1	1
0	1	0	1	1	1	0	0
0	1	1	1	1	1	1	1

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

How *many* $X = x$, $Y = y$, $Z = z$ s.t.

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x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1 ✓	1	0	0	1 ✓
0	0	1	0 ✗	1	0	1	1 ✓
0	1	0	1 ✓	1	1	0	0 ✗
0	1	1	1 ✓	1	1	1	1 ✓

$$\#\textbf{SAT} = 6$$

Satisfiability and Model Counting

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

How *many* $X = x$, $Y = y$, $Z = z$ s.t.

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x	y	z	$\phi(x, y, z)$	x	y	z	$\phi(x, y, z)$
0	0	0	1 ✓	1	0	0	1 ✓
0	0	1	0 ✗	1	0	1	1 ✓
0	1	0	1 ✓	1	1	0	0 ✗
0	1	1	1 ✓	1	1	1	1 ✓

$$\#\textbf{SAT} = 6$$

#P-complete

Normal Forms

CNF

Conjunctive Normal Form

$$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$$

Normal Forms

CNF

Conjunctive Normal Form

$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$

DNF

Disjunctive Normal Form

$(\neg Y_1 \wedge \neg Y_2) \vee (Y_3 \wedge Y_4)$

Normal Forms

CNF

Conjunctive Normal Form

$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$

DNF

Disjunctive Normal Form

$(\neg Y_1 \wedge \neg Y_2) \vee (Y_3 \wedge Y_4)$

NNF

Negation Normal Form

$\neg Z_1 \wedge (Z_2 \vee \neg Z_3) \vee Z_4$

Normal Forms

CNF

Conjunctive Normal Form

$(X_1 \lor \neg X_2) \land (\neg X_3 \lor X_4)$

DNF

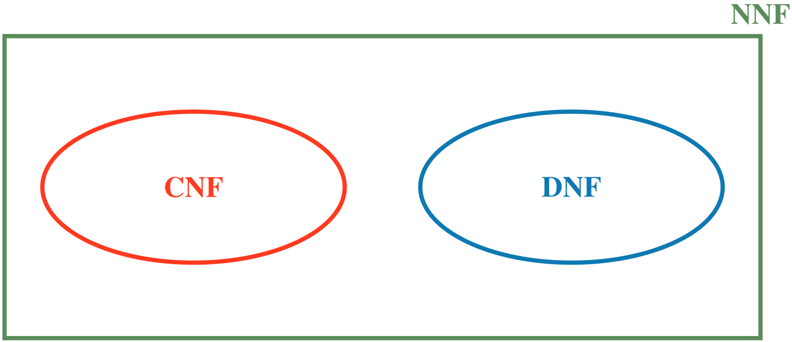
Disjunctive Normal Form

$(\neg Y_1 \land \neg Y_2) \lor (Y_3 \land Y_4)$

NNF

Negation Normal Form

$\neg Z_1 \land (Z_2 \lor \neg Z_3) \lor Z_4$



Normal Forms

CNF

Conjunctive Normal Form

$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$

DNF

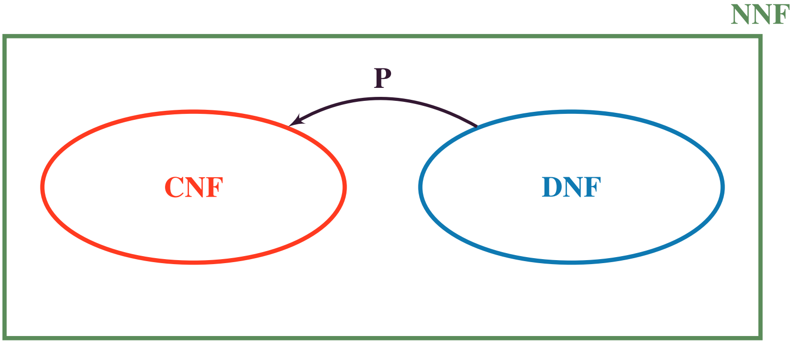
Disjunctive Normal Form

$(\neg Y_1 \wedge \neg Y_2) \vee (Y_3 \wedge Y_4)$

NNF

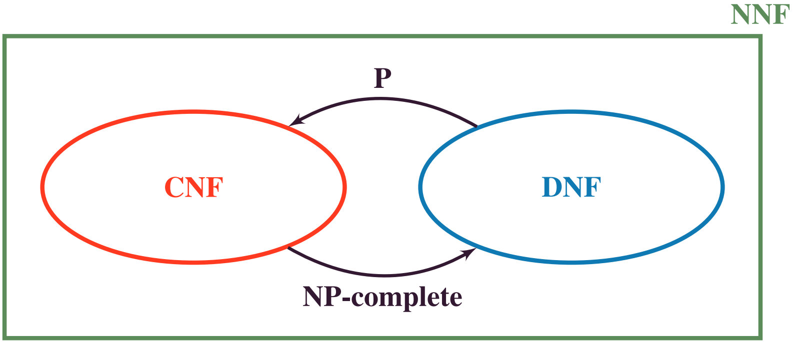
Negation Normal Form

$\neg Z_1 \wedge (Z_2 \vee \neg Z_3) \vee Z_4$



Normal Forms

CNF	**DNF**	**NNF**
Conjunctive Normal Form	Disjunctive Normal Form	Negation Normal Form
$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$	$(\neg Y_1 \wedge \neg Y_2) \vee (Y_3 \wedge Y_4)$	$\neg Z_1 \wedge (Z_2 \vee \neg Z_3) \vee Z_4$



Circuits?

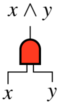
Circuits?

Circuits?

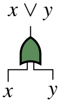
Logic Circuits

$x, y \in \{0, 1\}$

$x \wedge y \quad \Leftrightarrow$



$x \vee y \quad \Leftrightarrow$



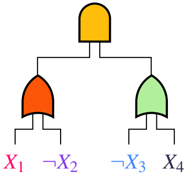
$\neg x \quad \Leftrightarrow$

Normal Forms in Logic Circuits

CNF

Conjunctive Normal Form

$$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$$

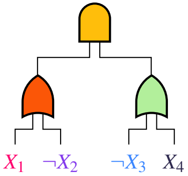


Normal Forms in Logic Circuits

CNF

Conjunctive Normal Form

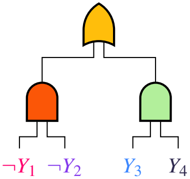
$(X_1 \vee \neg X_2) \wedge (\neg X_3 \vee X_4)$



DNF

Disjunctive Normal Form

$(\neg Y_1 \wedge \neg Y_2) \vee (Y_3 \wedge Y_4)$



Normal Forms in Logic Circuits

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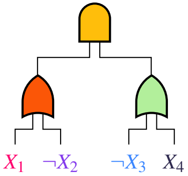

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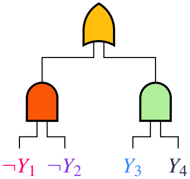
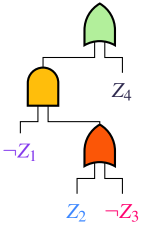


NNF

Negation Normal Form

$\neg Z_1 \wedge (Z_2 \vee \neg Z_3) \vee Z_4$



Satisfiability and Model Counting in Logic Circuits

$$\phi(X, Y, Z) = [X \wedge (\neg Y \vee Z)] \vee [(\neg Z \vee Y) \wedge \neg X]$$

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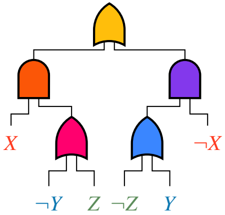

Satisfiability and Model Counting in Logic Circuits

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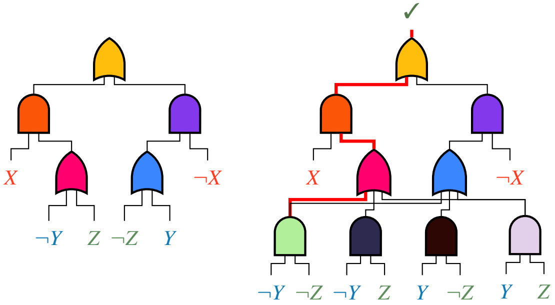

SAT $=$ ✓

Satisfiability and Model Counting in Logic Circuits

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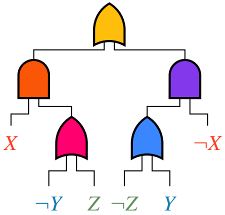

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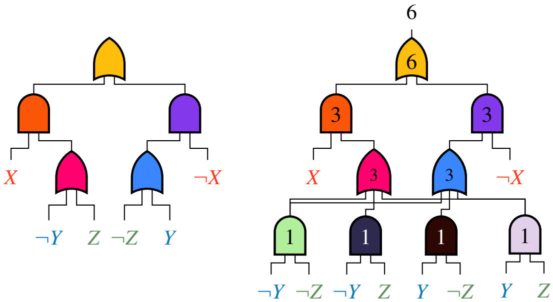
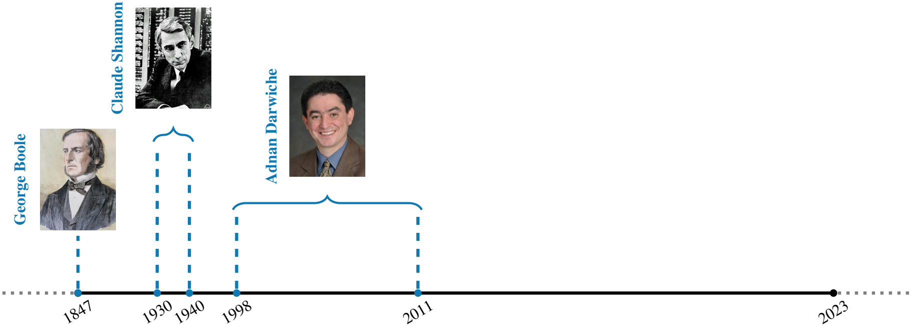


$$\#\textbf{SAT} = 6$$

Circuits?

Circuits?


George Boole
Claude Shannon
Adnan Darwiche
1847
1930
1940
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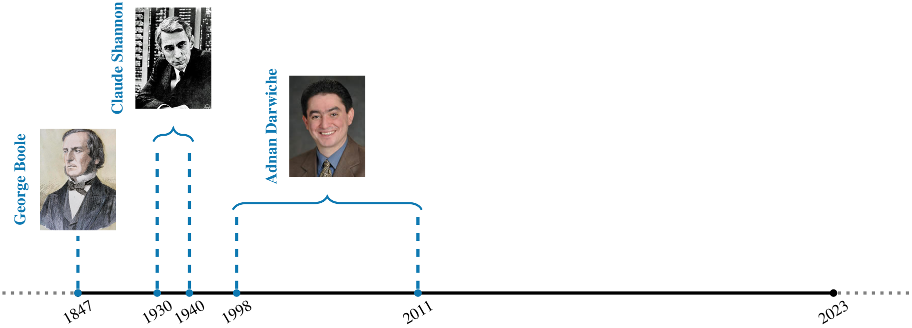
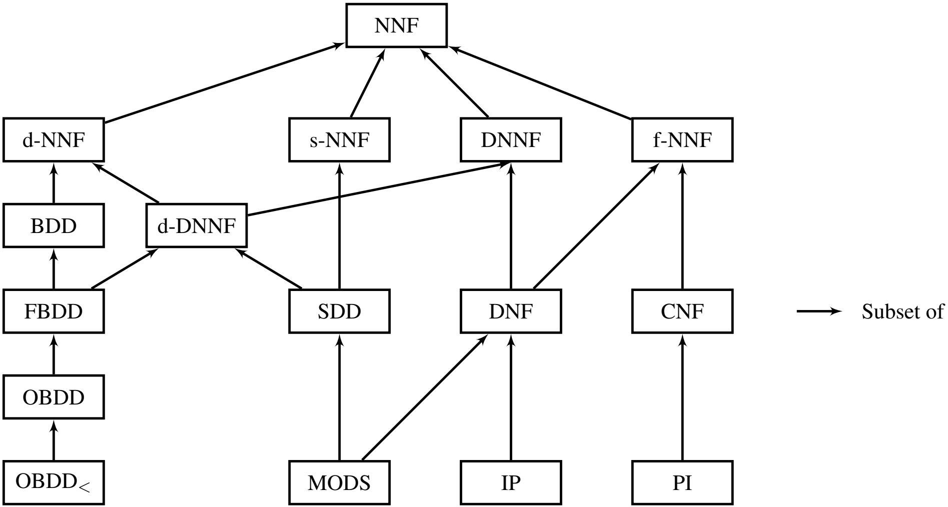
Circuits?



Knowledge Compilation

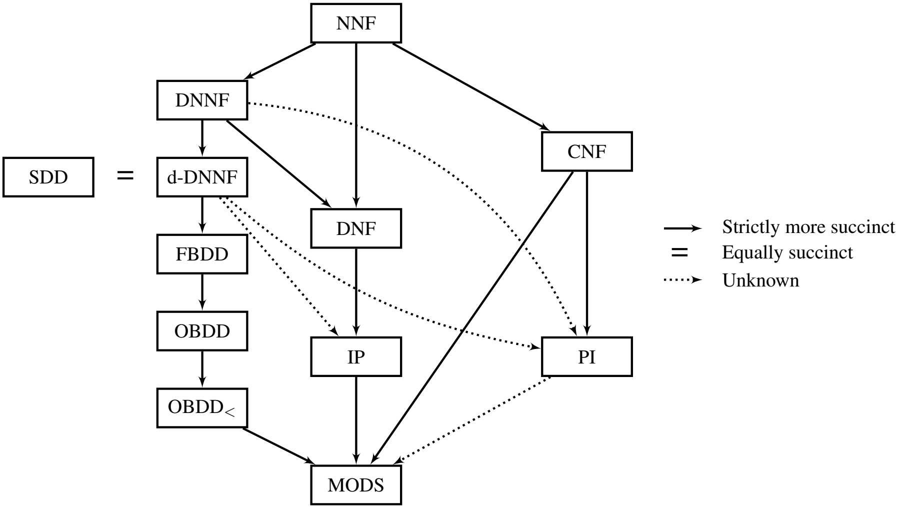
How much/many ... $\left\{ \begin{array}{l} \text{... **succinct** (i.e. *compact/efficient*) are circuits for ...} \\ \text{... **queries** in polytime are supported by ...} \\ \text{... **transformations** in polytime are available for ...} \end{array} \right\}$ ... different **classes** of **logic circuits**?

The World of Logic Circuits



[Darwiche and Marquis, 2002]

Succinctness in Logic Circuits



[Darwiche and Marquis, 2002]

Querying in Logic Circuits

L	CO	VA	CE	IM	EQ	SE	CT	ME
NNF	∘	∘	∘	∘	∘	∘	∘	∘
DNNF	✓	∘	✓	∘	∘	∘	∘	✓
d-NNF	∘	∘	∘	∘	∘	∘	∘	∘
s-NNF	∘	∘	∘	∘	∘	∘	∘	∘
f-NNF	∘	∘	∘	∘	∘	∘	∘	∘
d-DNNF	✓	✓	✓	✓	?	∘	✓	✓
SDD	✓	✓	✓	✓	?	∘	✓	✓
BDD	∘	∘	∘	∘	∘	∘	∘	∘
FBDD	✓	✓	✓	✓	?	∘	✓	✓
OBDD	✓	✓	✓	✓	✓	∘	✓	✓
$\text{OBDD}_<$	✓	✓	✓	✓	✓	✓	✓	✓
DNF	✓	∘	✓	∘	∘	∘	∘	✓
CNF	∘	✓	∘	✓	∘	∘	∘	∘
PI	✓	✓	✓	✓	✓	✓	∘	✓
IP	✓	✓	✓	✓	✓	✓	∘	✓
MODS	✓	✓	✓	✓	✓	✓	✓	✓

Notation	Query
CO	Consistency check
VA	Validity check
CE	Clausal entailment check
IM	Implicant check
EQ	Equivalence check
SE	Sentential entailment check
CT	Model counting
ME	Model enumeration

Notation	Description
✓	In P
✗	Not in P
∘	Not in P unless P $=$ NP
?	Unknown

[Darwiche and Marquis, 2002]

Transformations in Logic Circuits

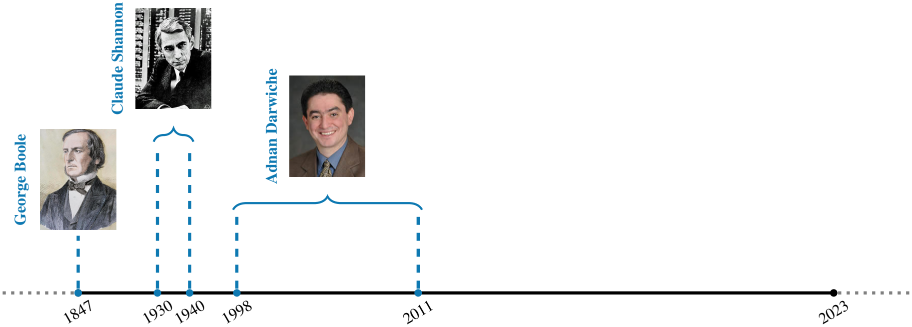
L	CD	FO	SFO	$\land$C	$\land$BC	$\lor$C	$\lor$BC	$\neg$C
NNF	✓	○	✓	✓	✓	✓	✓	✓
DNNF	✓	✓	✓	○	○	✓	✓	○
d-NNF	✓	○	✓	✓	✓	✓	✓	✓
s-NNF	✓	○	✓	✓	✓	✓	✓	✓
f-NNF	✓	○	✓	✗	✗	✗	✗	✓
d-DNNF	✓	○	○	○	○	○	○	✓
SDD	✓	○	○	○	○	○	○	✓
BDD	✓	○	✓	✓	✓	✓	✓	✓
FBDD	✓	✗	○	✗	○	✗	○	✓
OBDD	✓	✗	✓	✗	○	✗	○	✓
$\text{OBDD}_<$	✓	✗	✓	✗	✓	✗	✓	✓
DNF	✓	✓	✓	✗	✓	✓	✓	✗
CNF	✓	○	✓	✓	✓	✗	✓	✗
PI	✓	✓	✓	✗	✗	✗	✓	✗
IP	✓	✗	✗	✗	✓	✗	✗	✗
MODS	✓	✓	✓	✗	✓	✗	✗	✗

Notation	Query
CD	Conditioning
FO	Forgetting
SFO	Singleton forgetting
$\land$**C**	Conjunction
$\land$**BC**	Bounded conjunction
$\lor$**C**	Disjunction
$\lor$**BC**	Bounded disjunction
$\neg$**C**	Negation

Notation	Description
✓	In P
✗	Not in P
○	Not in P unless P $=$ NP
?	Unknown

[Darwiche and Marquis, 2002]

Circuits?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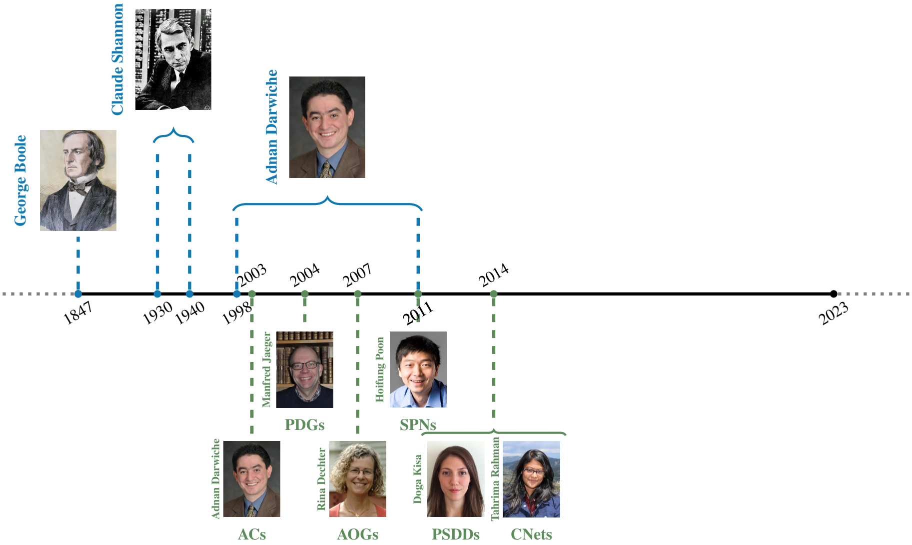
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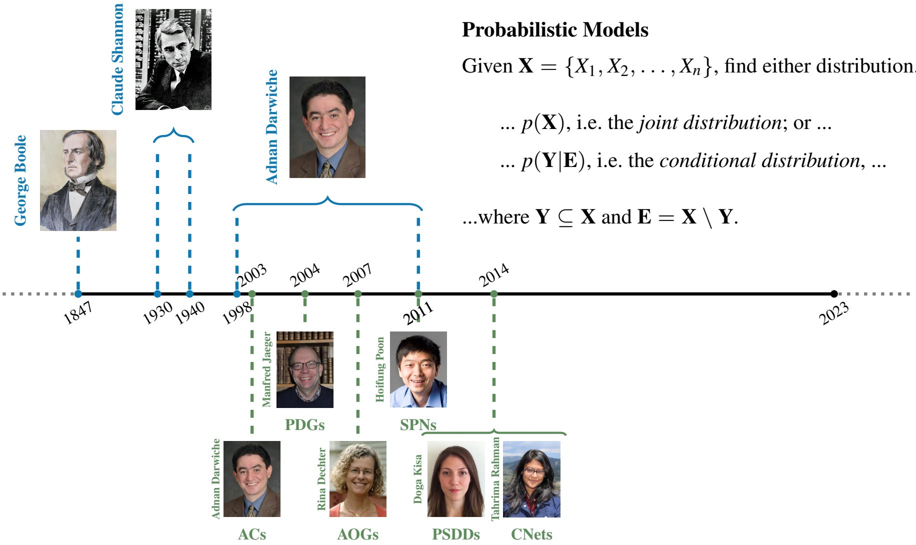
Manfred Jaeger
Hoifung Poon
PDGs
SPNs
Adnan Darwiche
Rina Dechter
Doga Kisa
Tahrima Rahman
ACs
AOGs
PSDDs
CNets

Circuits?



Probabilistic Models

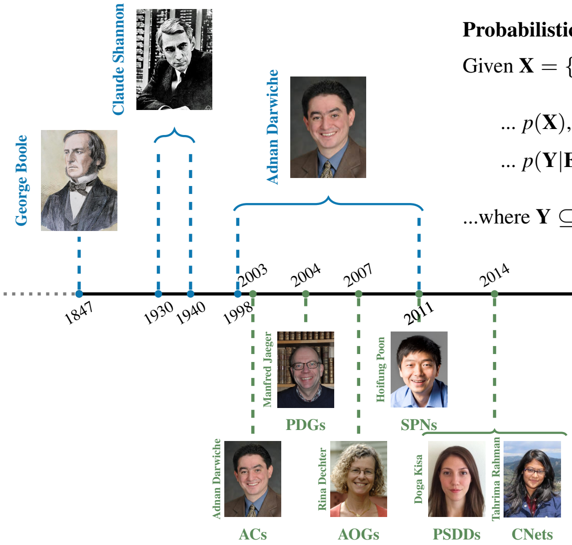
Given $\mathbf{X} = \{X_1, X_2, \ldots, X_n\}$, find either distribution...

... $p(\mathbf{X})$, i.e. the *joint distribution*; or ...

... $p(\mathbf{Y}|\mathbf{E})$, i.e. the *conditional distribution*, ...

...where $\mathbf{Y} \subseteq \mathbf{X}$ and $\mathbf{E} = \mathbf{X} \setminus \mathbf{Y}$.

Circuits?



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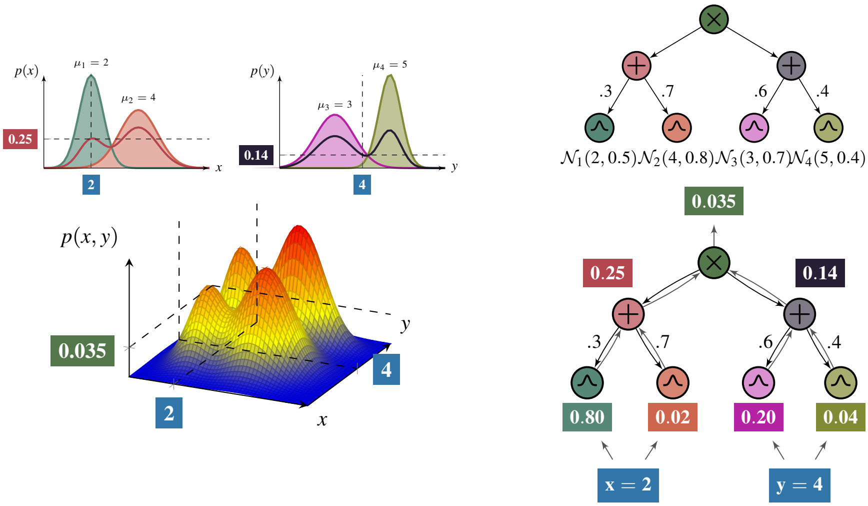
DISCRIMINATIVE

GENERATIVE

Probabilistic Circuits



Querying in Probabilistic Circuits

Query	+Sm?	+Dec?	+Det?	+Str Dec?
Evidence	✓	✓	✓	✓
Marginals	◦	✓	✓	✓
Conditionals	◦	✓	✓	✓
MPE	◦	◦	✓	✓
Shannon Entropy*	◦	◦	✓	✓
Rényi Entropy*	◦	◦	✓	✓
Cross Entropy*	◦	◦	◦	✓
Kullback-Leibler Div*	◦	◦	◦	✓
Rényi's Alpha Div*	◦	◦	◦	✓
Cauchy-Schwarz Div*	◦	◦	◦	✓
Logical Events	◦	◦	◦	✓
Mutual Information*	◦	◦	◦	✓

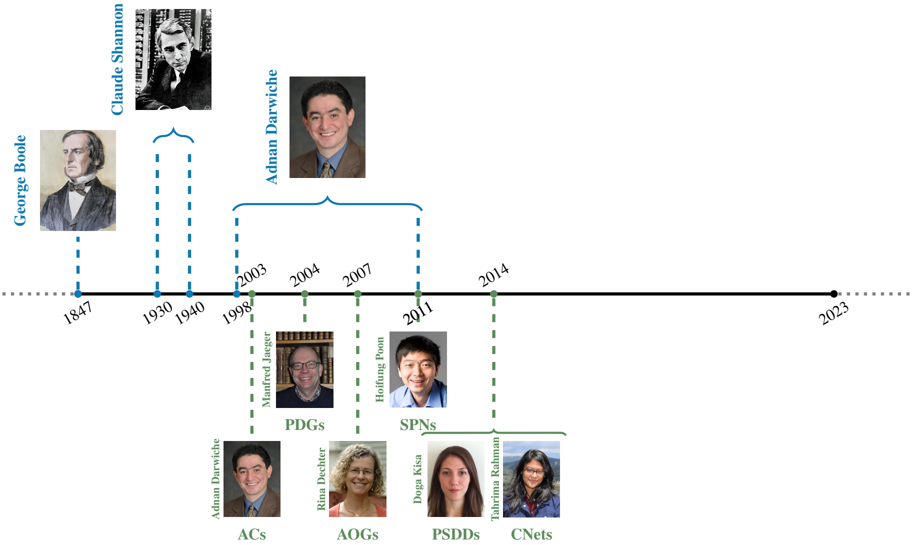
[Vergari et al., 2021, Poon and Domingos, 2011, Peharz et al., 2016, Conaty et al., 2017]

Transformations in Probabilistic Circuits

	Query	+Sm?	+Dec?	+Det?	+Str Dec?
Sum	$w_1 \cdot p + w_2 \cdot q$	✓	✓	∘	∘
Product	$p \cdot q$	∘	∘	∘	✓
Power	$p^n, n \in \mathbb{N}$	∘	∘	∘	✓
	$p^\alpha, \alpha \in \mathbb{R}$	∘	∘	✓	✓
Quotient	$\frac{p}{q}$	∘	∘	✓	✓
Log	$\log(p)$	∘	∘	✓	✓
Exp	$\exp(p)$	∘	∘	✓	✓

[Vergari et al., 2021]

Circuits?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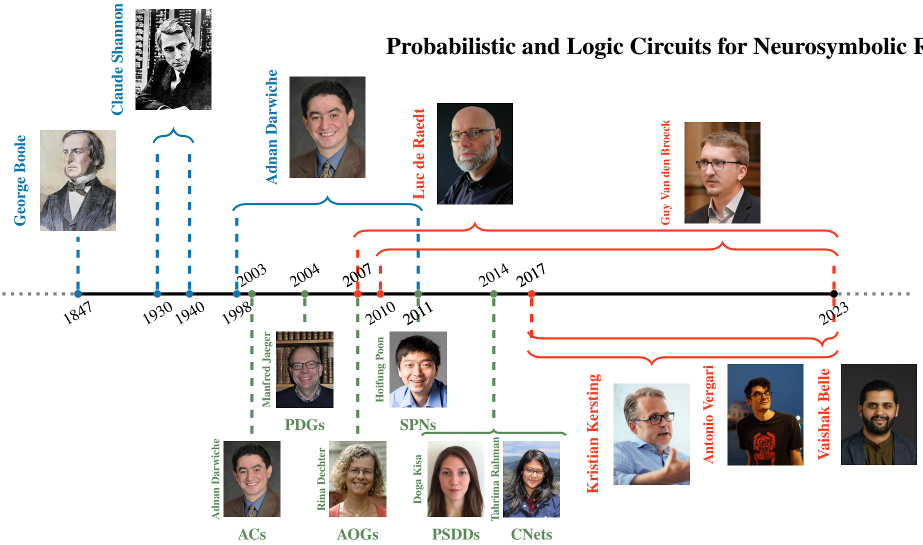
Circuits?

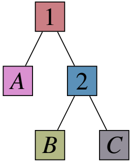
Probabilistic and Logic Circuits for Neurosymbolic Reasoning

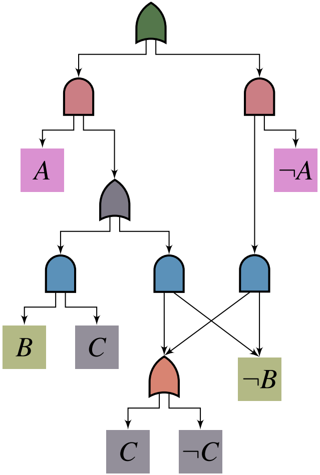


Logic Circuits $\subset$ Probabilistic Circuits

A	B	C	$\phi(\mathbf{x})$
0	0	0	1
1	0	0	1
0	1	0	0
1	1	0	0
0	0	1	1
1	0	1	1
0	1	1	0
1	1	1	1

$$\phi(A, B, C) = (A \vee \neg B) \wedge (\neg B \vee C)$$



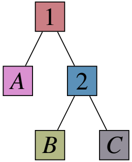


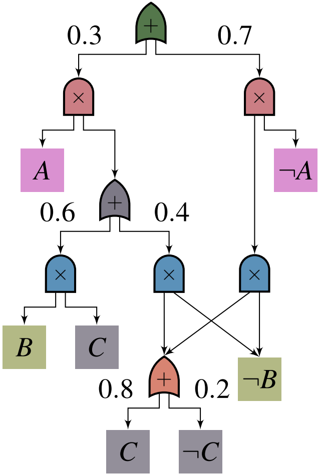
[Kisa et al., 2014]

Logic Circuits $\subset$ Probabilistic Circuits

A	B	C	$\phi(\mathbf{x})$	$p(\mathbf{x})$
0	0	0	1	0.140
1	0	0	1	0.024
0	1	0	0	0.000
1	1	0	0	0.000
0	0	1	1	0.560
1	0	1	1	0.096
0	1	1	0	0.000
1	1	1	1	0.180

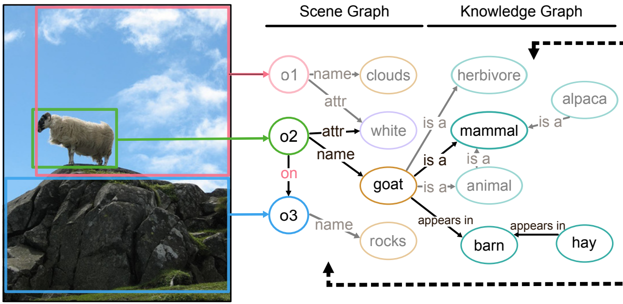
$$\phi(A, B, C) = (A \vee \neg B) \wedge (\neg B \vee C)$$





[Kisa et al., 2014]

Circuits in Visual Query Answering



SLASH Program

% knowledge graph
oa_rel("usually appears in", goat, barn).
oa_rel("usually appears in", hay, barn).
is_a(goat, mammal).
is_a(goat, animal).
is_a(goat, herbivore).
is_a(alpaca, herbivore).
is_a(mammal, animal).
name(N1, Oid) :-
name(N2, Oid), is_a(N2, N1).

% facts obtained from NPP's
name(o1, goat).
name(o2, rocks).
attr(o1, white).
attr(o2, gray).
relation(o1, o2, on).

Natural language question	Programmatic queries
"Identify the goat"	target(O):-name(O, goat).
"Identify the white mammal"	target(O):-name(O, mammal), attr(O, white).
"Identify the mammal on the rocks, that usually appears where hay appears"	target(O):- name(O, mammal), name(O2, rocks), relation(on, O, O2), oa_rel("usually appears in", O, P), oa_rel("usually appears in", hay, P).

difficulty

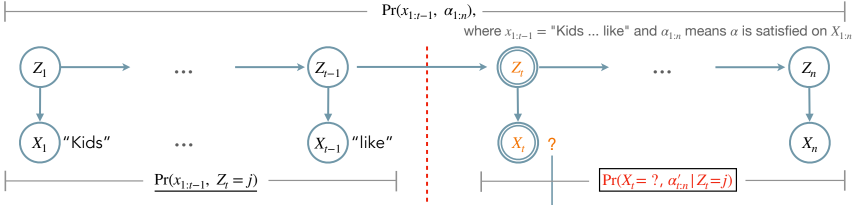
Answer

target(o2) 

[Skryagin et al., 2023]

Circuits in Natural Language Processing

Lexical Constraint $\alpha = \big(I(\text{like eating}) \vee I(\text{soccer})\big) \wedge I(\text{like working})$

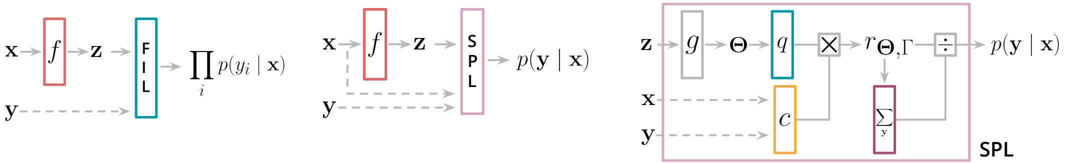


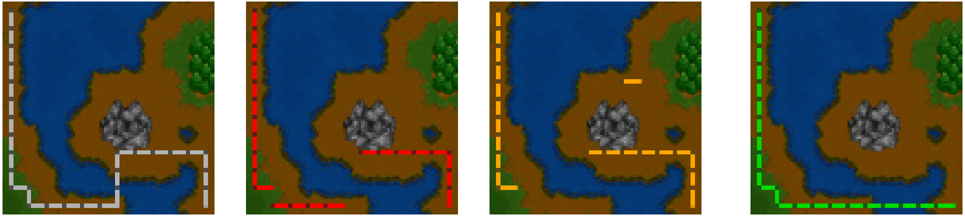
$\Pr(x_{1:t-1},\ \alpha_{1:n}) = (1) + (2) + (3)$

X_t	Recurrence	α'
"eating"	(1) $\Pr(x_{1:t-1}, X_t = \text{"eating"}, \alpha'_{t:n}) = \sum_j \underline{\Pr(x_{1:t-1}, Z_t = j)} \cdot \boxed{\Pr(X_t = \text{"eating"}, \alpha'_{t:n} \mid Z_t = j)}$	I(like working)
"working"	(2) $\Pr(x_{1:t-1}, X_t = \text{"working"}, \alpha'_{t:n}) = \sum_j \underline{\Pr(x_{1:t-1}, Z_t = j)} \cdot \boxed{\Pr(X_t = \text{"working"}, \alpha'_{t:n} \mid Z_t = j)}$	I(like eating) $\vee$ I(soccer)
else	(3) $\Pr(x_{1:t-1}, X_t \neq \text{"eating"}, X_t \neq \text{"working"}, \alpha'_{t:n})$ $= \Pr(x_{1:t-1}, \alpha'_{t:n}) - \Pr(x_{1:t-1}, X_t = \text{"eating"}, \alpha'_{t:n}) - \Pr(x_{1:t-1}, X_t = \text{"working"}, \alpha'_{t:n})$ $= \sum_j \underline{\Pr(x_{1:t-1}, Z_t = j)} \cdot \Big(\boxed{\Pr(\alpha'_{t:n} \mid Z_t = j)} - \boxed{\Pr(X_t = \text{"eating"}, \alpha'_{t:n} \mid Z_t = j)} - \boxed{\Pr(X_t = \text{"working"}, \alpha'_{t:n} \mid Z_t = j)}\Big)$	$\big(I$(like eating) $\vee$ I(soccer)$\big)$ $\wedge$ I(like working)

[Zhang et al., 2023]

Circuits in Neural Networks

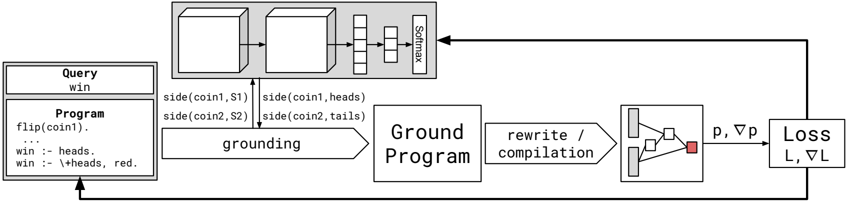




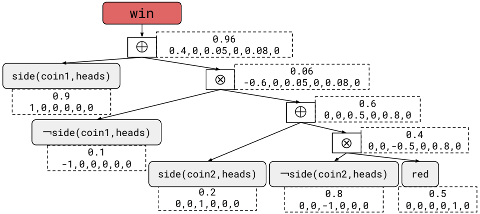
Ground Truth | FIL | Semantic Loss | Semantic Probabilistic Layer

[Ahmed et al., 2022]

Circuits in Deep Probabilistic Logic Programming

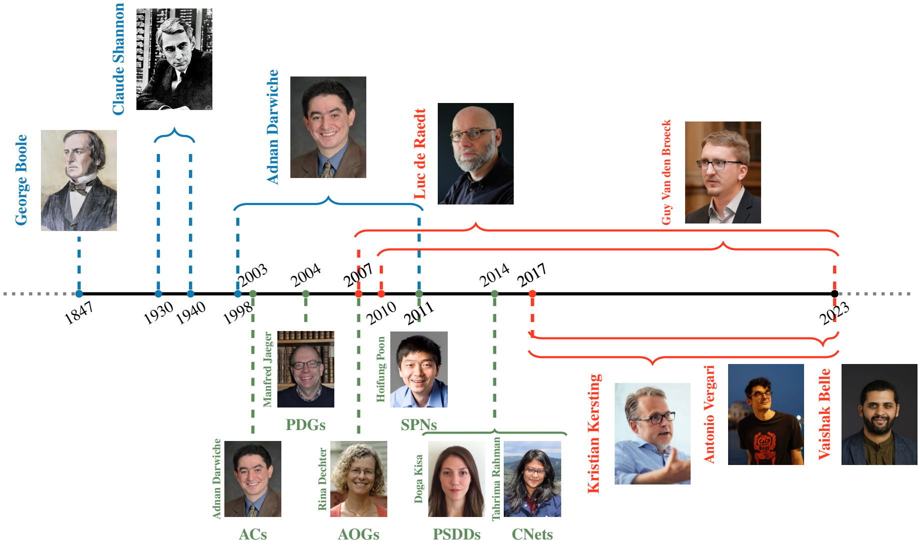



```
flip(coin1). flip(coin2).
nn(side,C,[heads,tails])::side(C,heads);
                          side(C,tails).
t(0.5)::red; t(0.5)::blue.
heads :- flip(X), side(X,heads).
win :- heads.
win :- \+heads, red.
query(win).
```



[Manhaeve et al., 2021]

Circuits?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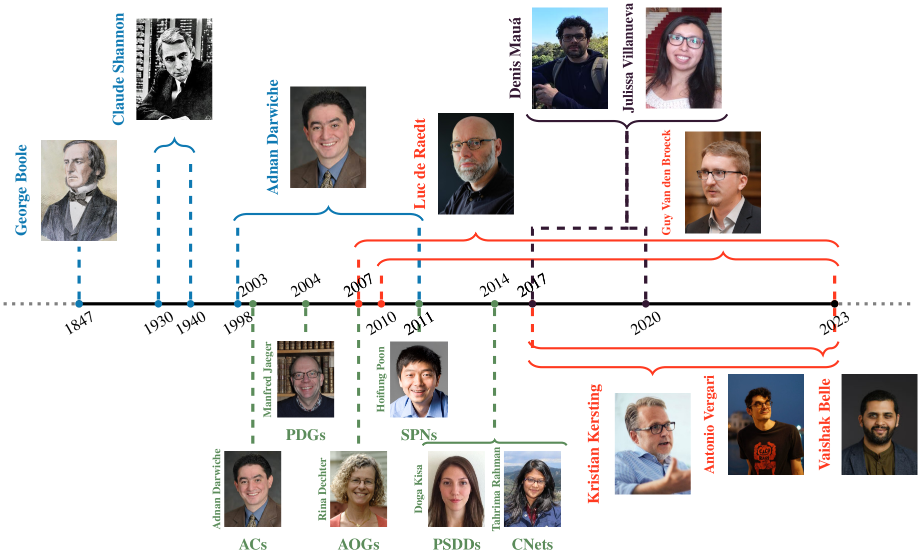
Circuits?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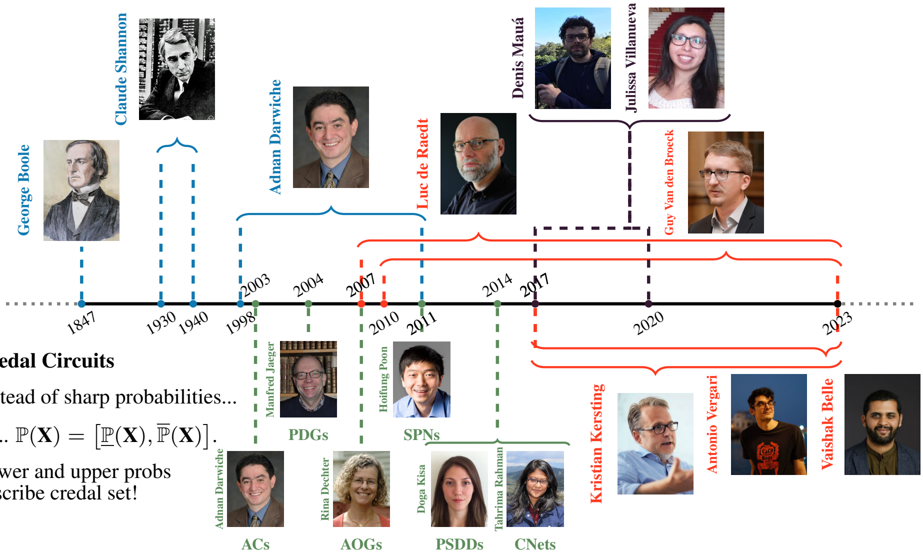


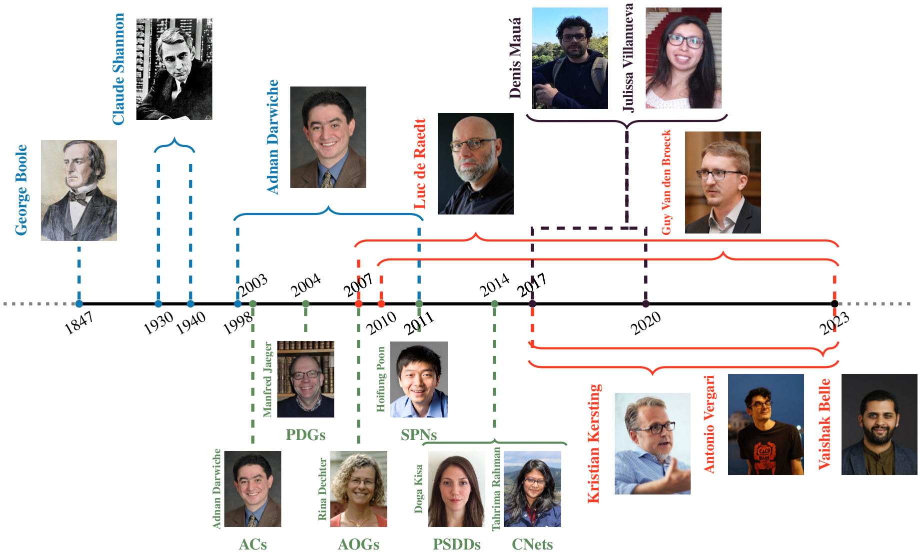
Credal Circuits

Instead of sharp probabilities...

... $\mathbb{P}(\mathbf{X}) = [\underline{\mathbb{P}}(\mathbf{X}), \overline{\mathbb{P}}(\mathbf{X})]$.

Lower and upper probs describe credal set!

Circuits?



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Thinking with Circuits

From Logic to Probabilistic and Back

Renato Lui Geh