A Fully Compositional Theory of Digital Circuits

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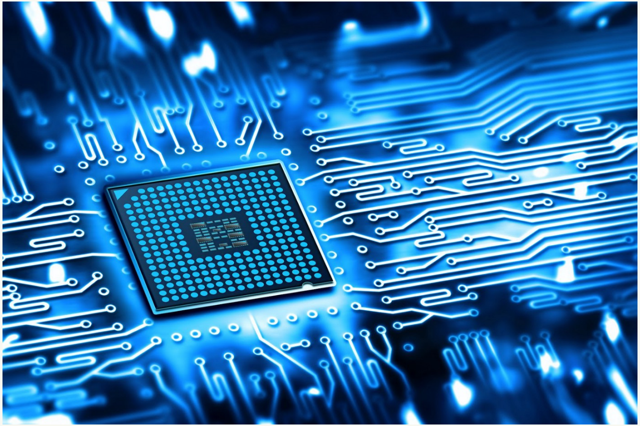
University of Birmingham

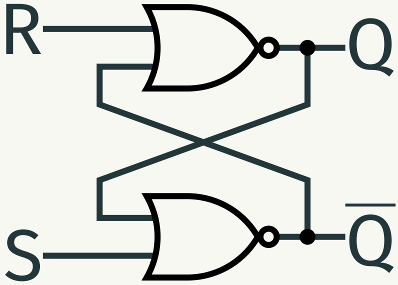
15 February 2024 – PPLV Research Seminar

What are we going to be talking about?

Digital circuits!

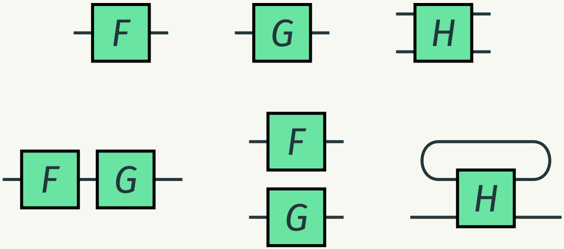


Digital circuits!



What are we going to be talking about?

We want a compositional theory of digital circuits.



Using string diagrams removes much of the bureacracy

(also they look pretty)

How did we get here?

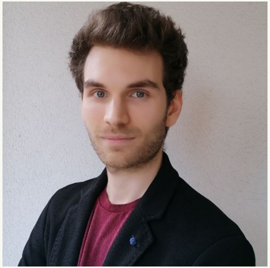
The story so far

2003

Yves Lafont

‘Towards an algebraic theory of Boolean circuits’

2016

Dan Ghica, Achim Jung, Aliaume Lopez

‘Diagrammatic semantics for digital circuits’

The story so far

‘Wow, this guy seems pretty groovy’

OCaml noises

2019

The story so far

'No'
'Okay'

'Do you know category theory'
'Do you want to do circuits stuff'

2021

The story so far

 +  = 

 +  = 

David Sprunger

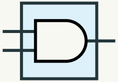
(now at Indiana State University)

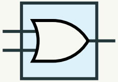
Let’s get dangerous

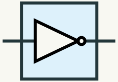


Combinational circuit components

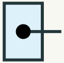
gates

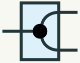

AND gate

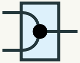

OR gate

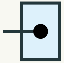

NOT gate

(co)monoid structure

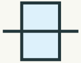

disconnected

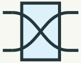

fork


join


stub

categorical structure


identity


symmetry

Light circuits 

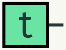
only contain gates and structure.

(actually, we do it more generally than this, but let's keep it simple)

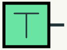
Sequential circuit components

Values

false



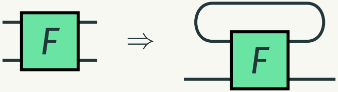
true



short circuit

Delay

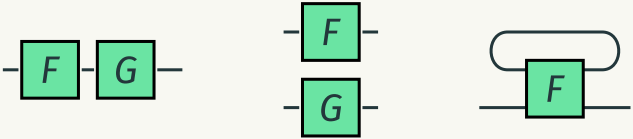
Feedback



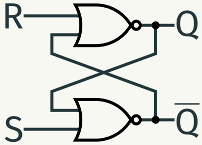
Dark circuits 

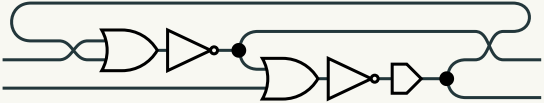
may contain delay or feedback.

Circuits are morphisms in a freely generated symmetric traced monoidal category (STMC).



Need an example?





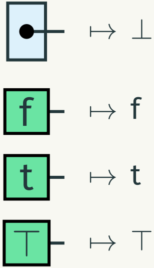
What is the meaning?

Denotational semantics

Interpreting the values

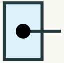
Values are interpreted in a lattice:

$$
\begin{tikzcd}[column sep=small]
 & \top \arrow[dl, dash] \arrow[dr, dash] & \\
t \arrow[dr, dash] & & f \arrow[dl, dash] \\
 & \bot &
\end{tikzcd}
$$

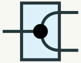


Let's make everything a function

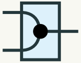
monotone functions $\overline{g} : \mathbf{V}^m \to \mathbf{V}$



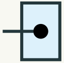
initialise $() \mapsto (\bot)$



copy $x \mapsto (x, x)$



join in the lattice $(x, y) \mapsto x \sqcup y$



discard $x \mapsto ()$

Feedback is interpreted as the least fixed point.

Functions are not enough

How do we model delay?

Streams!

Streams

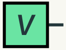
A stream $\mathbf{V}^\omega$ is an infinite sequence of values.

$$v_0 :: v_1 :: v_2 :: v_3 :: v_4 :: v_5 :: v_6 :: v_7 :: \cdots$$

A stream function $\mathbf{V}^\omega \to \mathbf{V}^\omega$ consumes and produces streams.

$$f(v_0 :: v_1 :: v_2 :: v_3 :: v_4 :: \cdots) = w_0 :: w_1 :: w_2 :: w_3 :: w_4 :: \cdots$$

Interpreting the sequential components



$$() := v :: \bot :: \bot :: \bot :: \cdots$$


$$(v_0 :: v_1 :: v_2 :: \cdots) := \bot :: v_0 :: v_1 :: v_2 :: \cdots$$

Maybe there are too many streams

Does every stream function $(\mathbf{V}^m)^\omega \to (\mathbf{V}^n)^\omega$ correspond to a circuit?

No.

(but this is to be expected!)

Restricting the stream functions

Circuits are causal.

They can only depend what they've seen so far.

Circuits are monotone.

They are constructed from monotone functions.

Is that all? Not quite... (but we'll get there)

Some operations on stream functions

Given a causal stream function $f \colon (\mathbf{V}^m)^\omega \to (\mathbf{V}^n)^\omega$ and an element $a \in \mathbf{V}^m$...

initial output $\quad f[a] \in \mathbf{V}^n$

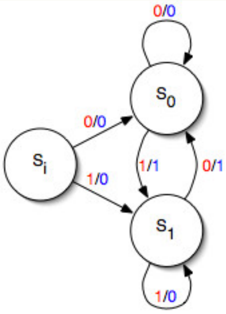
'the first thing f produces given a'

stream derivative $\quad f_a \in (\mathbf{V}^m)^\omega \to (\mathbf{V}^n)^\omega$

'how f behaves after seeing a first'

Hold on, these look familiar...

An old friend



Mealy machines!

Stream functions are the *states* in a Mealy machine.

Circuits have finitely many behaviours

Circuits have a finite number of components.

So there are finite number of states in the Mealy machine.

So the outputs of streams given some input must be periodic.

(There are finitely many stream derivatives).

These are the streams we're looking for

Theorem

A stream function is the interpretation of a sequential circuit if and only if it is ***causal, monotone*** *and has* ***finitely many stream derivatives.***

Sound and complete denotational semantics

Doing something useful

Suppose we have two circuits
with the same denotation

$$[\![-\boxed{F}-]\!] = [\![-\boxed{G}-]\!]$$

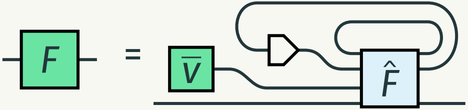
What does this tell us about the
structure of these circuits?

Operational semantics

We want to find a set of reductions for digital circuits

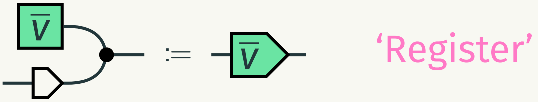
We want to reduce circuits to their outputs syntactically in a step-by-step manner

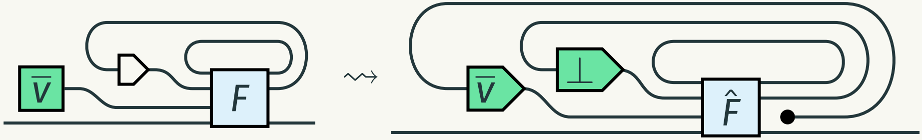
Going global

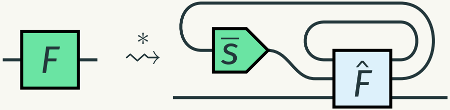


by moving boxes and wires around

Going global





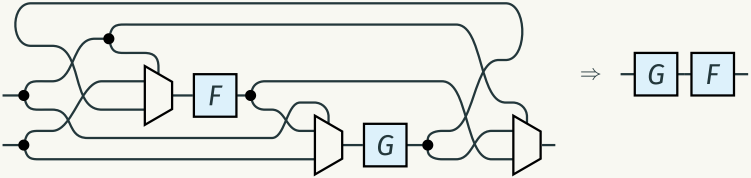


The sticking point

What are we going to do about the non-delay-guarded trace?

In industry, feedback is usually delay-guarded.

But this rules out some clever circuits!



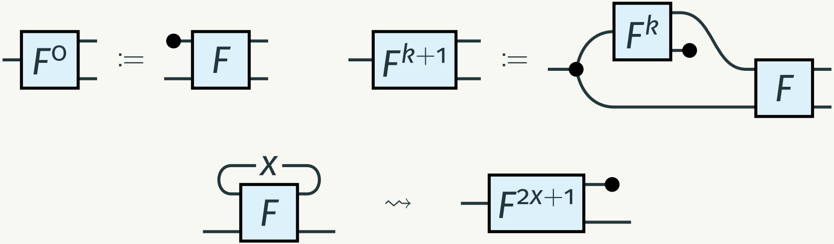
(And also it would be cheating)

V is a finite lattice...

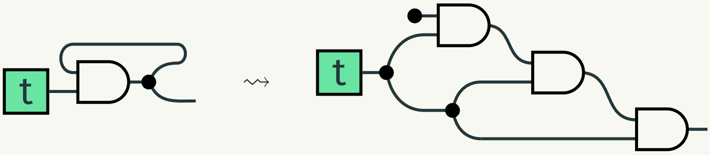
The functions are monotone...

We can compute the least fixed point
in finite iterations!

Getting rid of non-delay-guarded feedback



Getting rid of non-delay-guarded feedback



Here’s Mealy

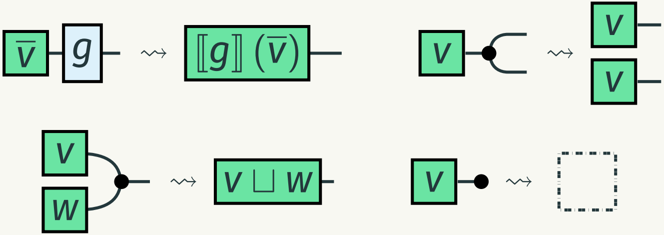
For any circuit

What is the goal

We want to compute the outputs of circuits given some inputs

How does a circuit process a value?

Reducing values

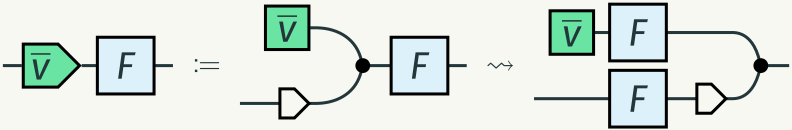


”

Lemma

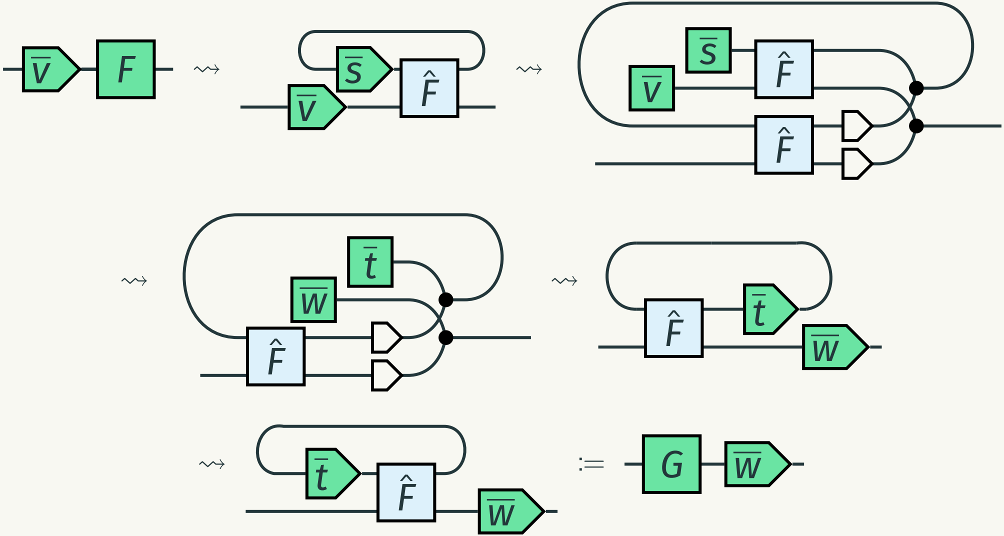
For every $\boxed{F}$ *there exists* $\boxed{\overline{w}}$ *s.t.* $\boxed{\overline{v}}\,\boxed{F} \rightsquigarrow \boxed{\overline{w}}$.

What about delays?



'Streaming'

Catching the jet stream



When are two circuits observationally equivalent?

Circuits have finitely many states...

Definition

Two circuits with at most c delay components are observationally equivalent if the reduction procedure creates the same outputs for all inputs of length $|\mathbf{V}|^c + 1$.

Observe this

Theorem

Two circuits are observationally equivalent if and only if they are denotationally equivalent.

Sound and complete operational semantics

Still takes a while

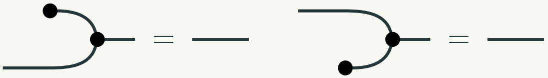
This is a superexponential upper bound for testing circuit equivalence

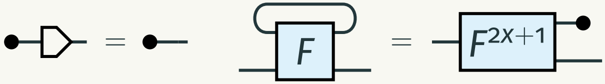
Can we do better?

Algebraic semantics

Mealy is so back

First things first...





By these equations,

It’s completely normal

We want a way to use equations to translate a circuit into another circuit with the same behaviour

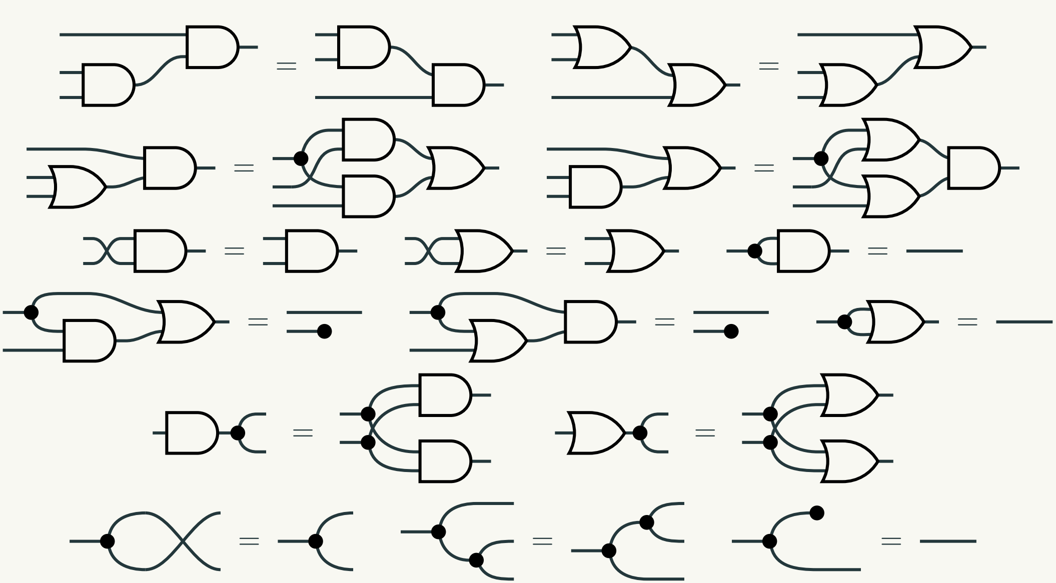
It's completely normal

Say we have a procedure $|-|$ for establishing a canonical circuit for a function $f : \mathbf{V}^m \to \mathbf{V}^n$

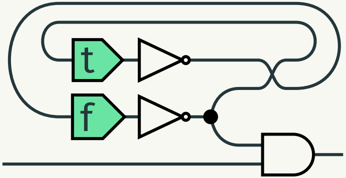
A circuit is normalised if it is in the image of $|-|$

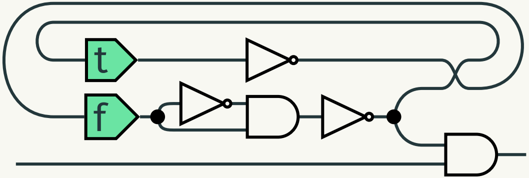
What equations are needed to normalise any circuit?

It's completely normal



Is this enough?

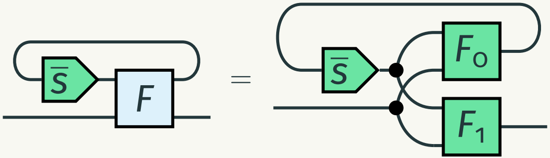




The cores may not have the same semantics!

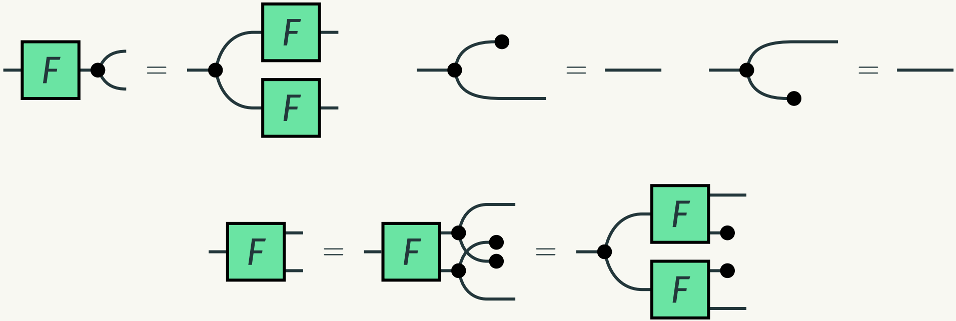
Idea: encode circuits so their state words have length equal to the number of states

Need to know the number of states: isolate the state transition and output

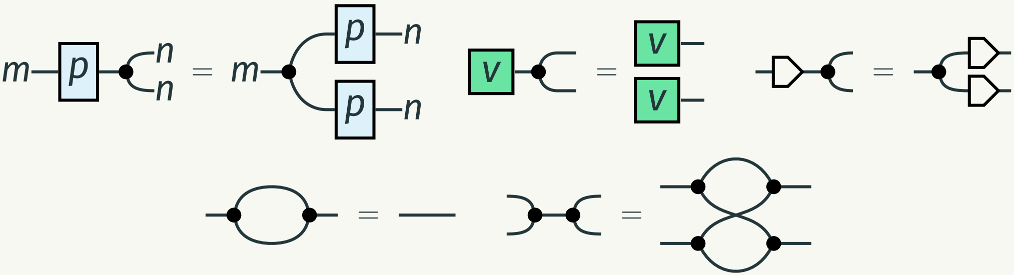


Cartesian doubt

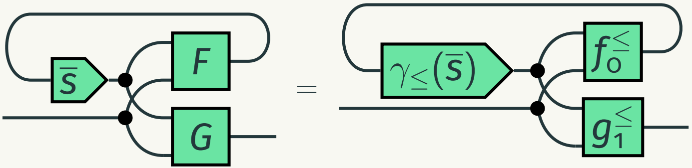
Need equations to make the fork natural and unital



Cartesian doubt



Now add an encoding equation



(I'm hiding some of the internal machinations here)

It is complete

By the completeness of the denotational semantics, each stream function has a corresponding encoded circuit...

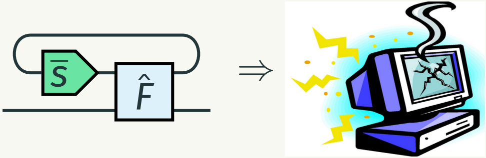
Theorem

Two circuits are equal by the equations if and only if they are denotationally equal.

Sound and complete algebraic semantics

Graph rewriting

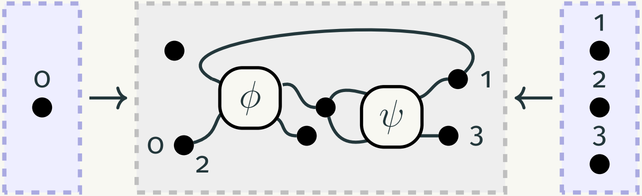
Making it combinatorial



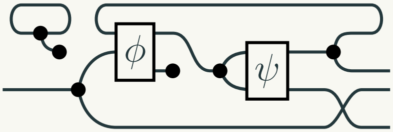
It is hard for computers to work with string diagrams...

...but computers love graphs!

A hyper kind of graph



There are correspondences between certain classes of hypergraphs and circuit string diagrams.



Using the correspondence

$$\begin{tikzcd}
\text{Circuit string diagram} \arrow[r] \arrow[d, equal] & \text{Hypergraph representation} \arrow[d, "\text{Graph rewrite}"] \\
\text{New circuit string diagram} & \text{Rewritten hypergraph} \arrow[l]
\end{tikzcd}$$

Implementing it all

The rewriting framework has been *implemented* in a hardware description language.

HUAWEI

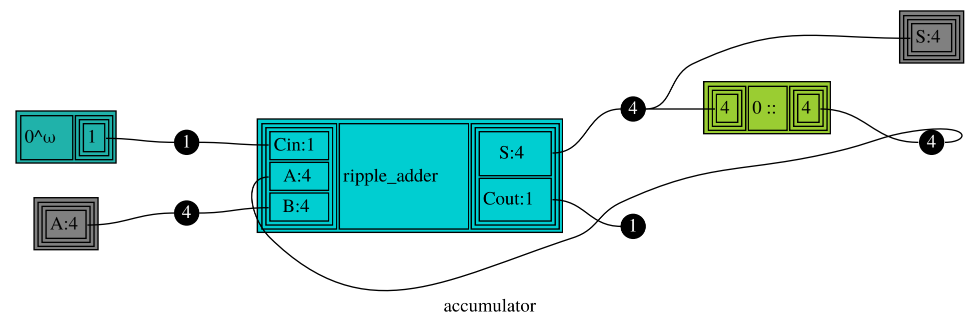
(the language is still in development)

(so I’ve been warned not to accidentally announce anything)

(also they changed everything so I can’t actually compile it at the moment)

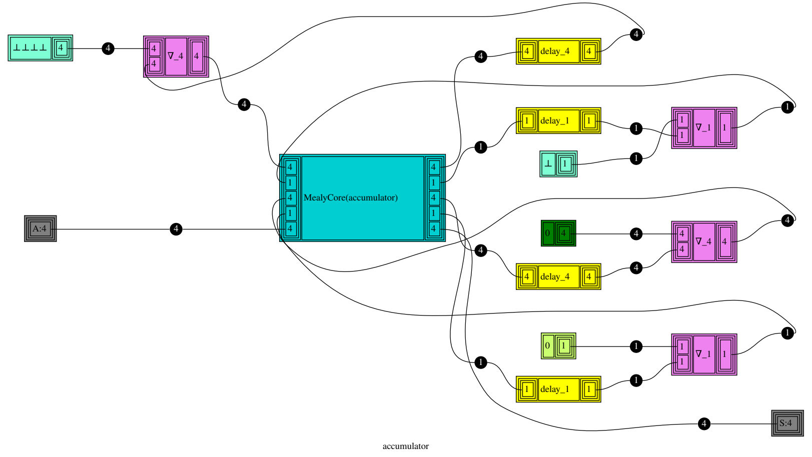
I can still show you something

Create a circuit...



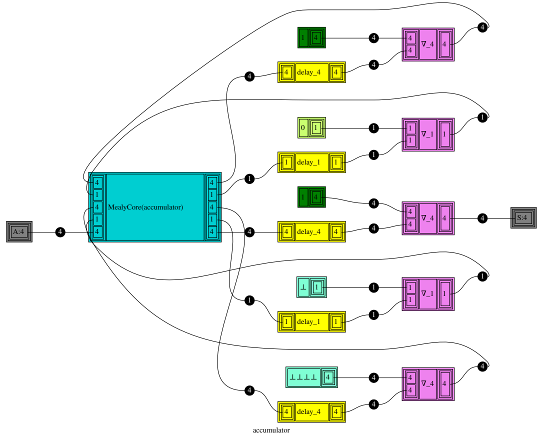
I can still show you something

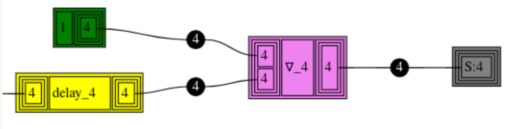
The evaluator converts it into Mealy form...



I can still show you something

…and then evaluates an input.





To the end

Three different semantics for sequential digital circuits

$$\begin{tikzcd}
& \text{Denotational} \arrow[dl, leftrightarrow, "\cong"'] \arrow[dr, leftrightarrow, "\cong"] & \\
\text{Operational} \arrow[rr, leftrightarrow, "\cong"'] & & \text{Algebraic}
\end{tikzcd}$$

Can adapt for automatic reasoning using graph rewriting