Tutorial

Introduction to Asynchronous Circuits and Systems

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What are Asynchronous Circuits?

❑ They are circuits that are not synchronous!

❑ Synchronous: Circuits that use a clock to separate consecutive system states from one another.

❑ Asynchronous: Circuits that define states in terms of input values and internal actions

Another Definition

❑ Synchronous: Time Domain

- Assert signals at a specific time, and for a specific duration

❑ Asynchronous: Sequence Domain

- Assert signals after some event, and retain until some other event

What Are They Good For?

❑ Top Ten List (From Al Davis, Async94)

Asynchronous Advantages, Often Cited:

-
-
-

Top Ten List - Async Advantages

1: Achieve Average Case Performance

- Exploit data-dependent processing times
- Best if difference between average and worst case is large
- Be careful not to spend too much time on completion detection

Top Ten List - Async advantages

2: Consume power only when needed

- CMOS, in particular, consumes power only during transitions
- Clocks make a *lot* of transitions, not all of them do useful work
- Demonstrated ability for async circuits to consume power only on demand

3: Provide easy modular composition

- LEGO™ approach
- Allows incremental improvement
- Object-oriented approach to hardware
- Operating parameter robustness

Top Ten List - Async Advantages

4: Do not require clock alignment at interfaces

- Synchronizing an incoming signal to a clock requires great care, and wastes time
- Metastability can cause hard-to-find errors
- Naturally adaptive to a variety of data rates

5: Metastability has time to resolve

- Any bistable device can get caught in a metastable region for an unpredictable amount of time
- Assuming fixed resolution time leaves possibility of errors
- Arbiters can be used to ensure correctness

Top Ten List - Async Advantages

6: Avoid clock distribution problems

- Major design time drain
- Major power budget drain
- Major chip area drain

7: Exploit concurrency more gracefully

- Natural way to describe systems with lots of concurrency
- Let concurrency happen rather than plan all interleavings

Top Ten List - Async Advantages

8: Provide intellectual Challenge

- Lots of good puzzles
- Informal reasoning is dangerous
- Room for innovation

9: Exhibit intrinsic elegance

- Provide direct mapping of sequence domain
- Tangible target for theoretical work
- Correct-by-construction design
- Measurement vs. trust

Top Ten List - Async Advantages

10: Global synchrony does not exist anyway!

- High clock speeds, large chips, and even larger systems
- Global synchrony is a useful abstraction, but it’s not reality
- May as well admit it, and figure out where async techniques can help solve problems

A Trio of Taxonomies

❏ Timing Models

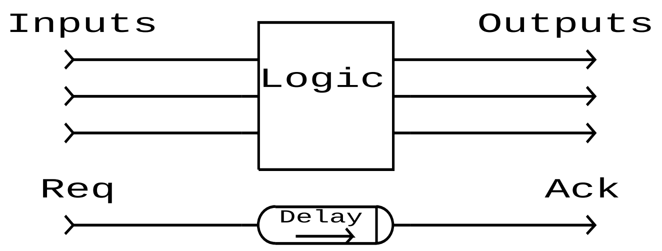
❏ Signaling Protocols

❏ System Specification and Structure

Taxonomy #1: Timing Models

❏ Bounded Delays

- Similar to synchronous circuits
- Measure maximum delay of each circuit piece, or assume a range of delays
- Model with extra delay (if required)

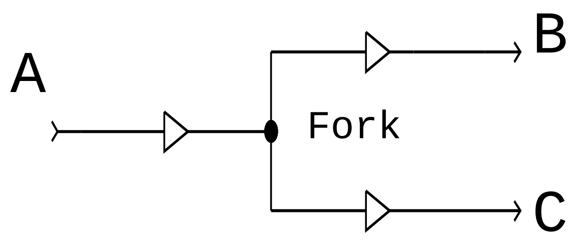


More Timing Models

- Speed Independent Circuits
  - Arbitrary delays in gates
  - Wires have no delay
- Delay Insensitive
  - Arbitrary delays on gates *and* wires
  - Very appealing model, but the class of circuits for which this really holds is small

Even More Timing Models

- Quasi Delay Insensitive
  - Delay insensitive, but with *isochronous forks*
  - Delay in isochronous forks assumed to be similar
  - In practice, very close to Speed Independent

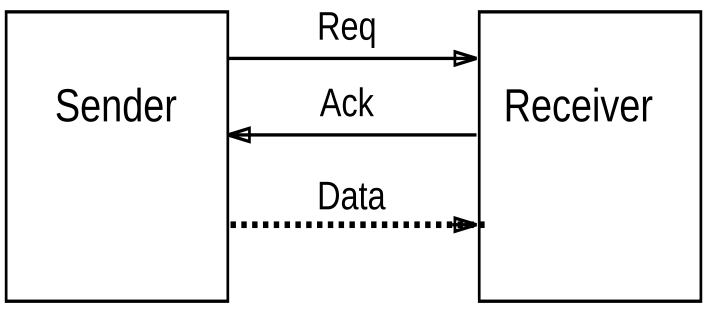


Combinations of Timing Models

- In practice, SI or DI within a range of delay possibilities seems useful
- Careful design of circuit modules can allow DI assumption at interface, SI, qDI, or Bounded Delay inside modules
- Use Bounded Delay for data path, some other model for control (i.e. Bundled Data)

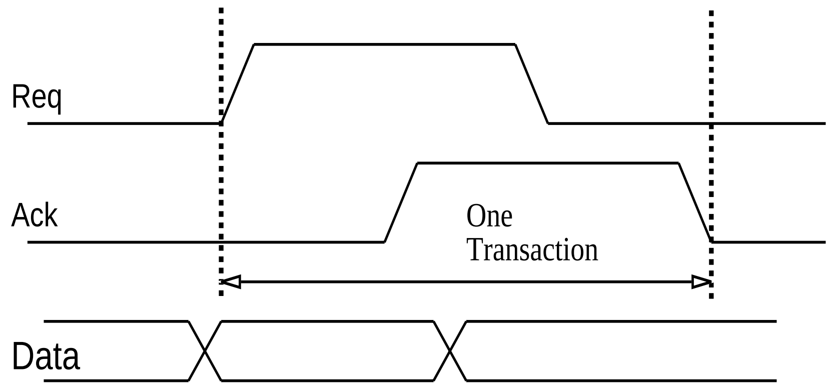
Taxonomy #2: Signaling Protocols

- Layer a protocol on top of signal transitions
- Request/Acknowledge is a popular structure
- Usually referred to as *Self-Timed*



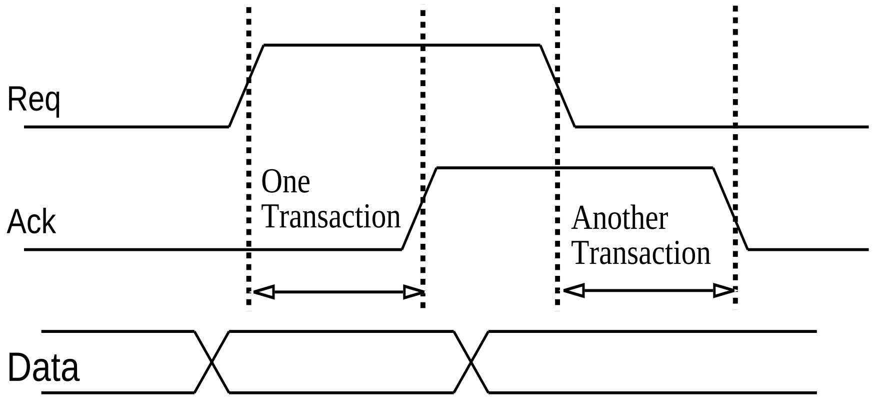
Control Signaling

- ❏ Four-Phase / Return to Zero / Level Signaling
- ❏ Specific protocol determines data release point



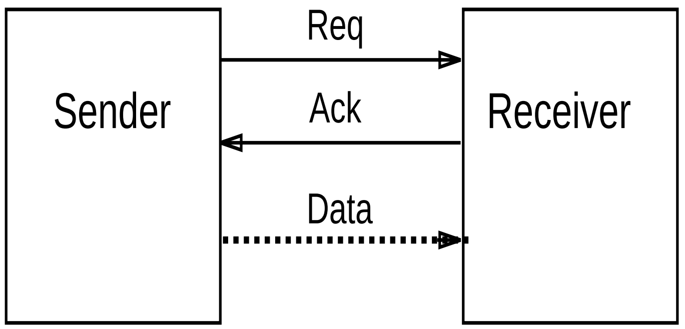
Control Signaling

- ❏ Two-Phase / Non-Return to Zero / Transition Signaling)



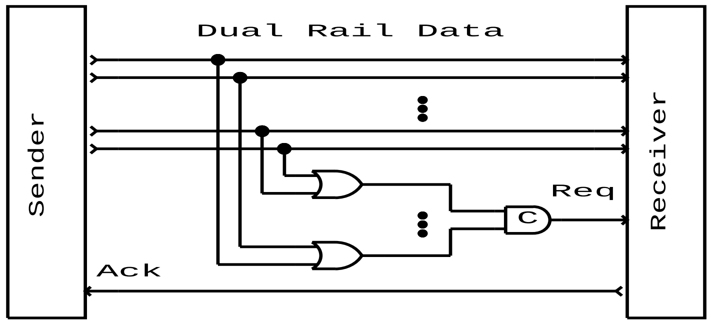
Data Signaling

- ❏ Bundled Data
  - "Normal" data wires, one per bit
  - Associated control that signals validity of data



Data Signaling

- ❏ Dual-Rail Data
  - Two wires per bit, encoded to show validity
  - 00 = no data, 01 = 0, 10 = 1, 11 = error (4Φ)
  - Single acknowledge control wire



Possible Combinations

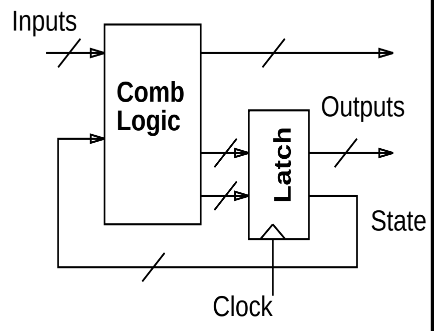
	Bundled	Dual-Rail
Four-Phase	Amulet 2	Martin synthesis Tangram
Two-Phase	Micropipelines Amulet 1	LEDR

Taxonomy #3: System Specification and Structure

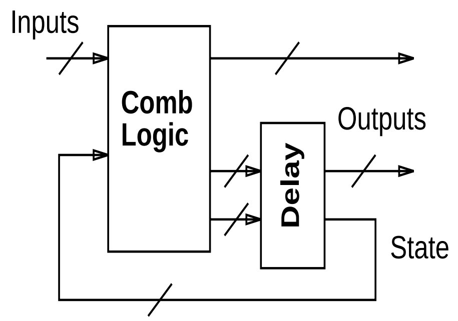
- *Finite State Machine*
- Petri-Net Based
- Macromodules
- Syntax-Directed Program Translation

Finite State Machines

- Classical asynchronous technique
- Huffman-style state machine



Synchronous State Machine



Huffman Async State Machine

Asynchronous FSM Models (AFSM)

- Fundamental mode operation
  - After an input change, AFSM must settle into new stable state before the next input change
  - Similar to setup and hold restrictions in synchronous machines
- Different conditions on input changes
  - Single input change (SIC)
  - Multiple input change (MIC)
  - Unrestricted input change (UIC)

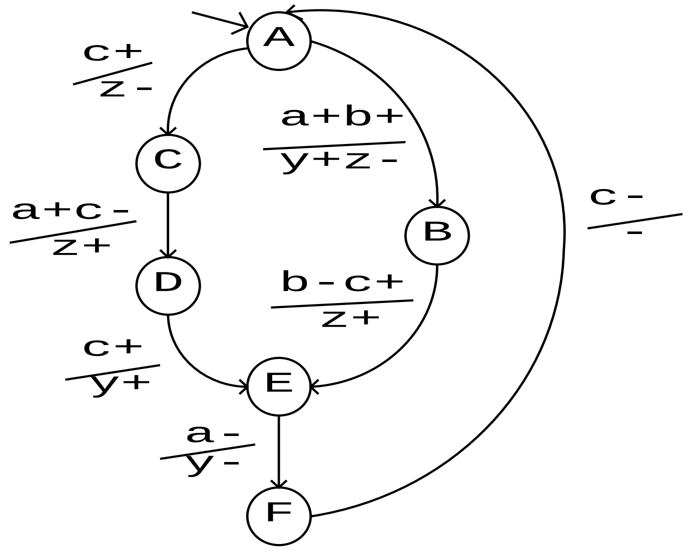
AFSM Design Method

- ❑ Generate primitive flow table
- ❑ Minimize states => reduced flow table
- ❑ Do state assignment
- ❑ Generate logic
  - Logic must be hazard-free for every input transition (under some input model and timing model)

Extending AFSM to Burst Mode

- ❑ Problem: SIC is too slow, MIC is too hard, UIC is *much* too hard.
  - SIC forces too much sequencing
- ❑ Solution: Operate in fundamental mode, but on *bursts* of inputs rather than single inputs
  - Allow inputs to change in any order inside the burst
  - A burst of outputs may be required
  - Outputs must be allowed to settle before another input burst is allowed

Burst Mode AFSM



Burst Mode Properties

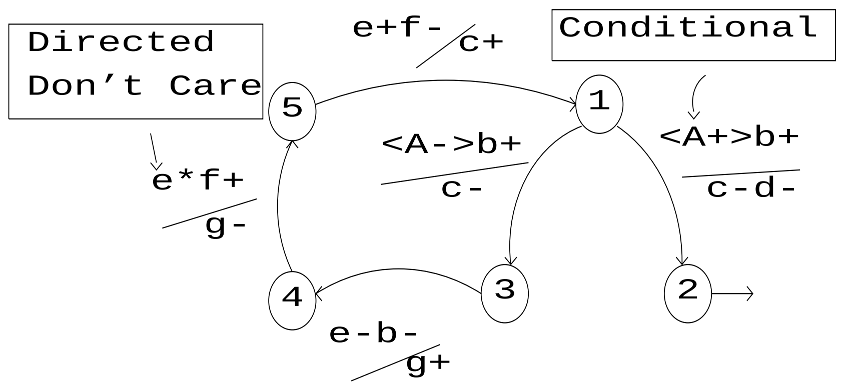
- ❑ Bursts follow a set of rules:
  - Inputs in burst may arrive in any order and at arbitrary times
  - Each state has a unique entry point
  - No input burst may be a subset of another in a given state
- ❑ Various techniques to build the circuits: locally clocked, unclocked, 3-D machines

Extended Burst Mode

Add a couple of features to burst mode specifications:

- ❑ Directed don’t-cares
  - Input edges that may or may not occur
  - Terminated by a definitive transition
- ❑ Level condition signals
  - Level signals that are sampled to determine state change direction
  - Must be distinct from transition signals

Extended Burst Mode Notation



Taxonomy #3: System Specification and Structure

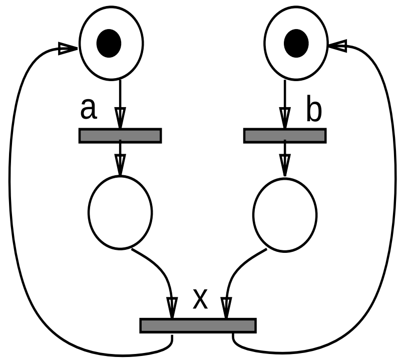
- ❑ Finite State Machine
- ❑ *Petri-Net Based*
- ❑ Macromodules
- ❑ Syntax-Directed Program Translation

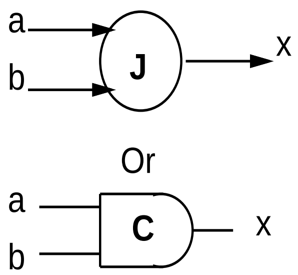
Techniques Based on Petri Nets

- ❑ These techniques are based on signal transitions (i.e. traces), rather than on system states
- ❑ Traces are a representation of the interface behavior of a circuit
- ❑ Petri-net based methods includes I-nets, Signal Transition Graphs (STG), Change Diagrams, Commands, etc...

I-nets (Interface Nets)

- Petri nets with transitions labeled with interface signal names



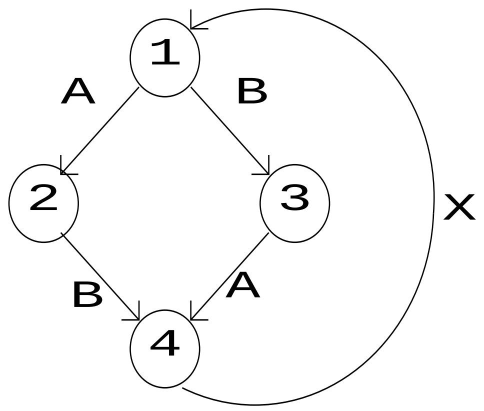


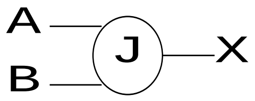
I-net Descriptions

- The I-net describes the allowed interface behavior
- Note that it may impose restrictions on the environment
- Can be translated into a state machine for implementation (I-net => Interface State Graph (ISG))

ISG Model

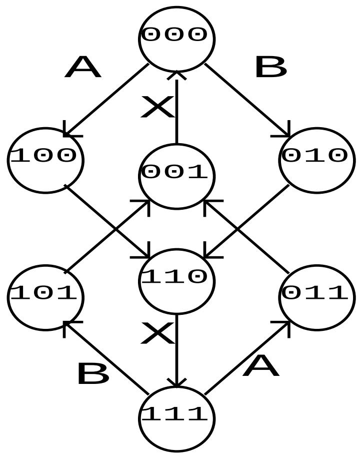
- Execute the I-net to generate ISG

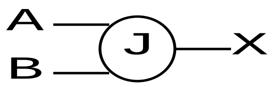




Encoded ISG (EISG)

- Encode states of the ISG

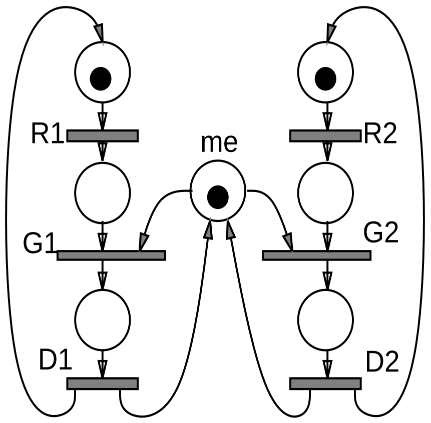


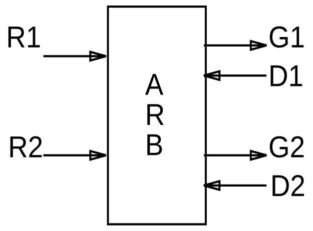


State Vector is ABX

I-net Generality

❑ Very general specification, can describe choice





Signal Transition Graphs

Like I-nets, STGs focus on interface signal transitions, but:

❑ Use graph theory to reason about properties represented in the STG

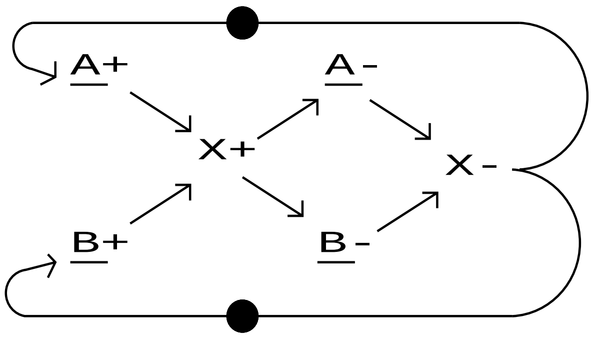
❑ Restrict the allowable forms of STGs such that they are implementable

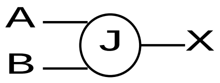
❑ Signal transitions are annotated with directions

Example STG

❑ Underlined signals are inputs

❑ Balls are like Petri-net tokens





Properties of STGs

❑ Can be checked for liveness (deadlock free), persistency (hazard free)

❑ Requires only syntactic check of the STG

❑ A live, persistent STG can be implemented as a speed-independent circuit

❑ STGs have been extended to handle various forms of choice, and to check for many more properties that influence behavior and circuits

Taxonomy #3: System Specification and Structure

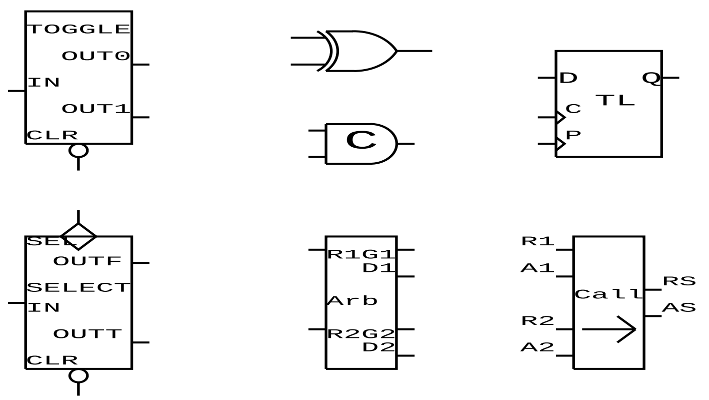
- ❑ Finite State Machine
- ❑ Petri-Net Based
- ❑ *Macromodules*
- ❑ Syntax-Directed Program Translation

Macromodules

- ❑ Like standard cells (the LEGO™ approach)
- ❑ A set of building blocks that can be assembled into asynchronous systems
- ❑ Usually considered delay-insensitive at the module interface
- ❑ Module internals designed using one of the previously defined techniques

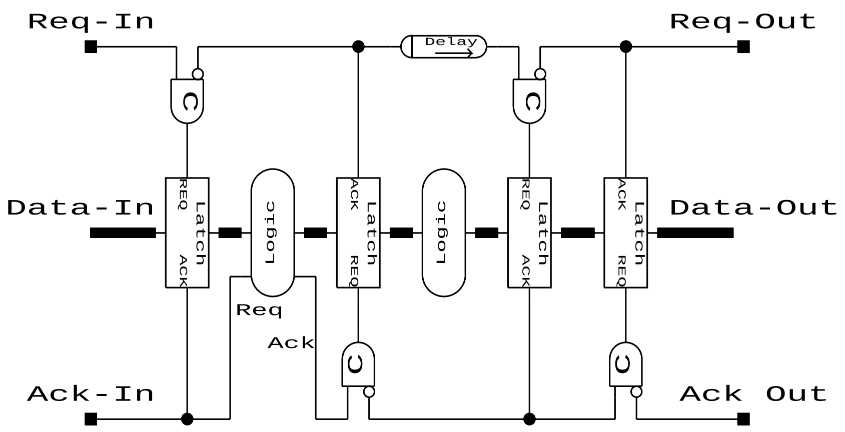
Sutherland's Micropipelines

- ❑ Popular macromodule library
- ❑ Two-phase transition signaling



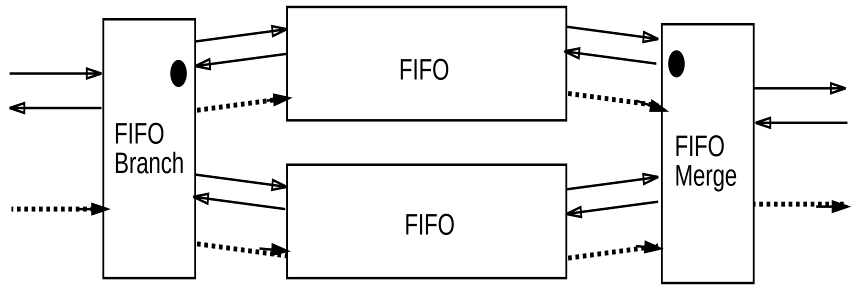
Basic Micropipeline

- ❑ Looks like a FIFO with processing

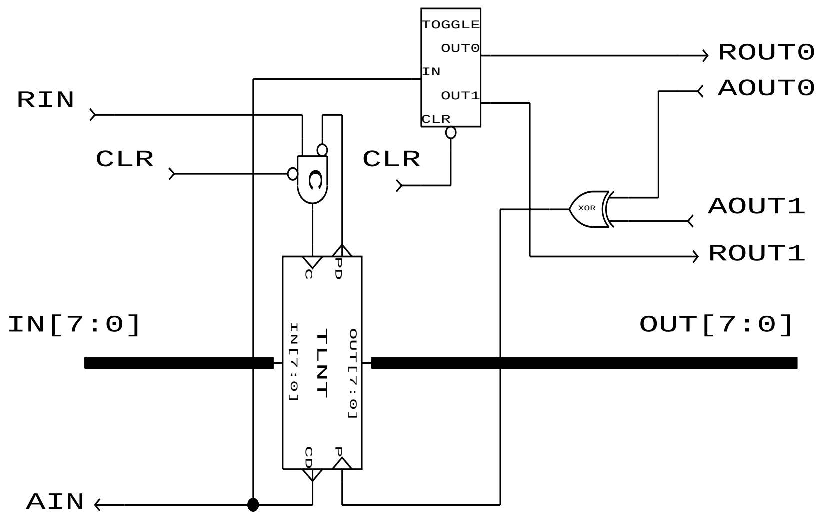


More Complicated Circuits

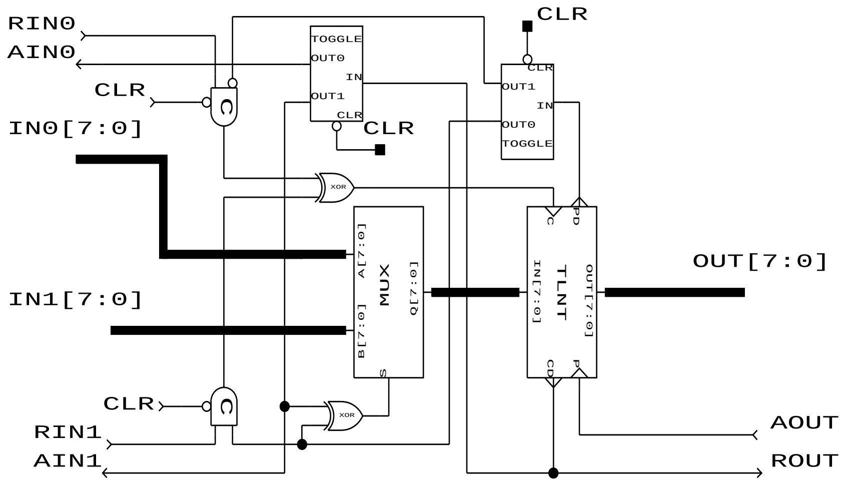
❑ Branching and Merging FIFOs



FIFO Toggle Branch



FIFO Toggle Merge



Taxonomy #3: System Specification and Structure

- ❑ Finite State Machine
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- ❑ *Syntax-Directed Program Translation*

Syntax Directed Program Translation

- ❑ Start with program description
- ❑ Translate to asynchronous circuit automatically
- ❑ Program notation should be capable of describing concurrency
- ❑ Basic communication structure is a *channel*
- ❑ CSP, OCCAM, and Tangram are popular starting points

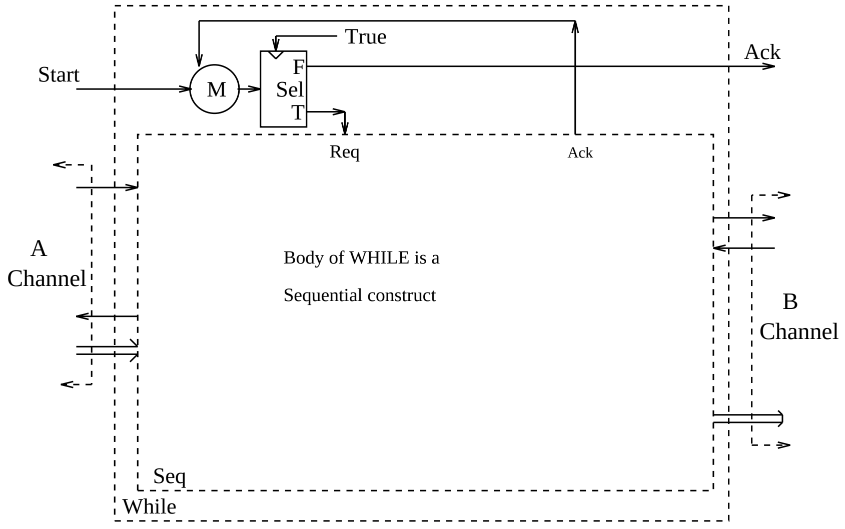
Overview of One Method

- ❑ Write an OCCAM program
- ❑ Use syntax-directed translation from that program to a collection of macromodules
- ❑ Perform peephole optimization of that circuit
- ❑ Place and route resulting circuit

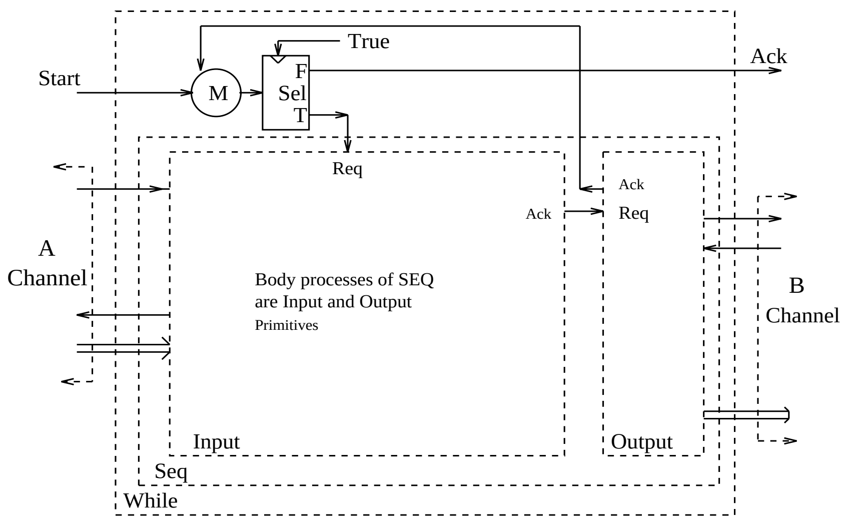
Example: FIFO Buffer

```
(PROC buffer ((CHAN A B))   ; define a buffer
   (WHILE TRUE              ; repeat forever
      (SEQ ((VAR temp<8>))  ; do in sequence
         (? A temp)         ; input from A
         (! B temp))))      ; output to B


; define a parallel composition of two buffers

(PAR ((CHAN input mid output))
   (buffer input mid)
   (buffer mid output))
```

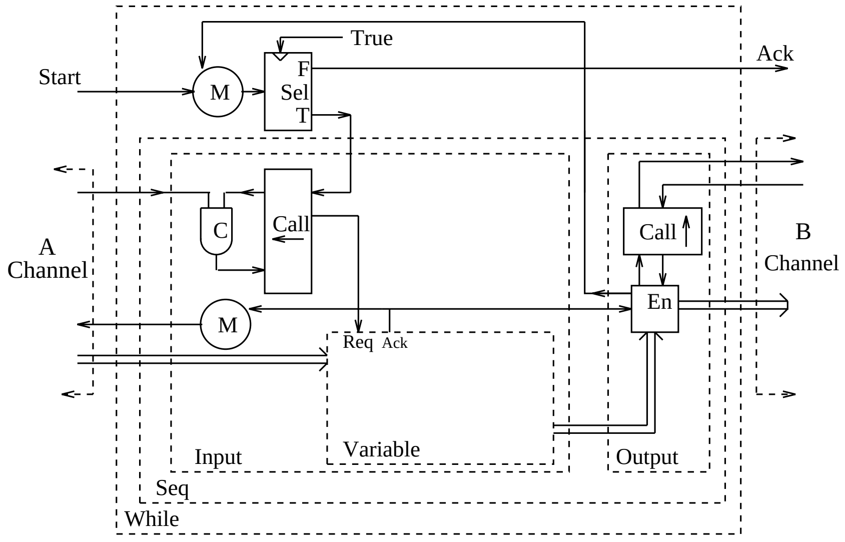
FIFO Buffer Translation 1



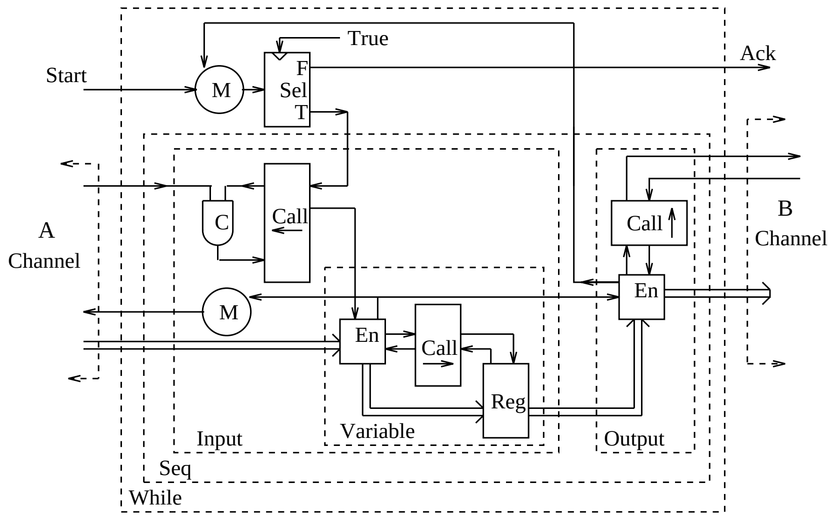
FIFO Buffer Translation 2



FIFO Buffer Translation 3



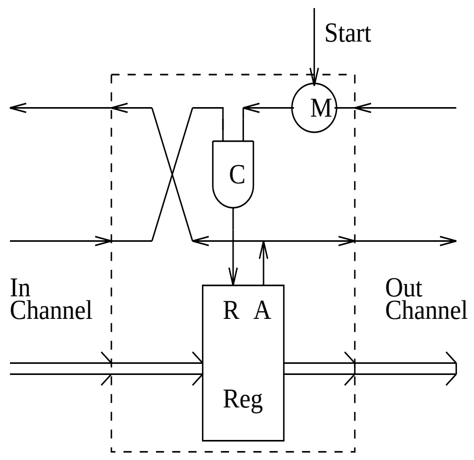
FIFO Buffer Translation 4



Peephole Optimization

- Identify circuit structure that can be improved
- Substitute “better” circuit

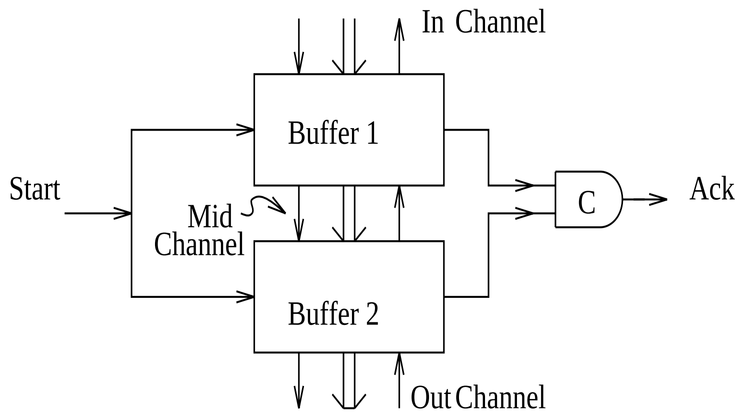
Optimized FIFO Circuit



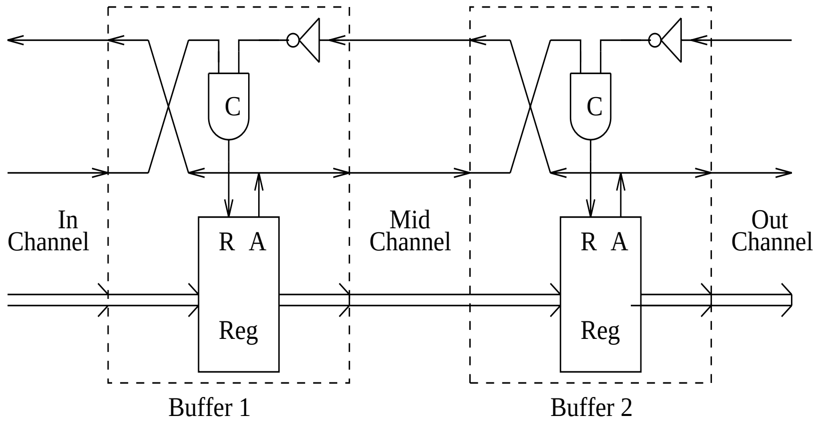
Recall the Program Text

```
(PROC buffer ((CHAN A B))   ; define a buffer
  (WHILE TRUE               ; repeat forever
    (SEQ ((VAR temp<8>))    ; do in sequence
      (? A temp)            ; input from A
      (! B temp))))         ; output to B


; define a parallel composition of two buffers

(PAR ((CHAN input mid output))
  (buffer input mid)
  (buffer mid output))
```

Parallel Composition



Final Circuit



Program Transformation

- ❑ Higher level description
- ❑ Correct by compilation circuits
- ❑ Lots of variations on this scheme
  - Different specification languages
  - Different libraries
  - Different compilation strategies

Conclusions (at last!)

- ❑ Asynchronous circuits research area is becoming too large to talk about in an hour!
- ❑ Topics that I have not talked about
  - Formal methods
  - Verification
  - Testing
  - Circuit techniques
  - Arbitration
  - Synchronous-Asynchronous interfacing
  - Datapath design
  - Low power circuits
  - Large case studies and landmark results

More Conclusions

- ❑ Asynchronous circuits and systems seem to have some compelling advantages
- ❑ So far, most are just potential, not demonstrated
- ❑ Don't be misled by the Top Ten List. There are plenty of significant problems left to solve!

Required Reading List

- ❑ S. Unger. *Asynchronous Sequential Switching Circuits*, Wiley-Interscience, 1969
- ❑ T. Chaney and C. Molnar. Anomalous behavior of synchronizer and arbiter circuits, *IEEE Transactions on Computers*, April 1973
- ❑ C. Seitz. System Timing, Chapter 7 of *Introduction to VLSI Systems* by Mead and Conway, 1980
- ❑ I. Sutherland. Micropipelines, *Communications of the ACM*, June 1989

Supplemental Reading List

❑ Finite State Machines

- S. M. Nowick and D. L. Dill. Automated synthesis of locally-clocked asynchronous state machines, *ICCAD-91*
- S. M. Nowick and D. L. Dill. Exact two-level minimization of hazard-free logic with multiple-input changes, *ICCAD-92*
- K. Y. Yun and D. L. Dill. Unifying synchronous/ asynchronous state machine synthesis, *ICCAD-93*
- A. Marshall, B. Coates, and P. Siegel. The design of an asynchronous communications chip, *IEEE Design and Test*, Summer 1994

Supplemental Reading List

❑ Petri-Net Based Approaches

- C. Molnar, T. Fang, and F. Rosenberger. Synthesis of delay-insensitive modules. In *Chapel Hill Conference on VLSI*, 1985
- T.-A. Chu. Synthesis of self-timed VLSI circuits from graph-theoretic specifications. Ph.D. Thesis, MIT, (Technical Report MIT-LCS-TR-393)
- T. Meng, R. Broderson, and D. Messerschmitt. Automatic synthesis of asynchronous circuits from high-level specifications. *IEEE Transactions on CAD*, Nov. 1989
- M. Kishinevsky, A. Kondratyev, A. Taubin, and V. Varshavsky. *Concurrent Hardware: The Theory and Practice of Self-Timed Design*. John Wiley and Sons, 1993.

Supplemental Reading List

❑ Macromodules

- W. Clark. Macromodular computer systems. In *Proceedings of the Spring Joint Computer Conference. AFIPS*, April 1967
- I. Sutherland, R. Sproull, I. Jones. Standard Asynchronous Modules. Technical Memo #4662, Sutherland, Sproull, and Associates, 1986
- J. Ebergen. A formal approach to designing delay-insensitive circuits. *Distributed Computing* 5(3), 1991
- S. Furber, P. Day, J. Garside, N. Paver, J. Woods. A Micropiplined ARM. in *Proceedings of VLSI '93*, Grenoble, 1993

Supplemental Reading List

❑ Program Translation Approaches

- A. Martin. Compiling communicating processes into delay insensitive circuits. *Distributed Computing*, 1(3), 1986
- S. Burns and A. Martin. Syntax-directed translation of concurrent programs into self-timed circuits. In *Fifth MIT Conference on Advanced Research in VLSI*, 1988
- K. van Berkel and R. Saeijs. Compilation of communicating processes into delay-insensitive circuits. *ICCD-88*
- E. Brunvand and R. Sproull. Translating concurrent programs into delay-insensitive circuits, *ICCAD-89*

Further Pointers

- ❏ This list only scratches the surface. For further pointers, try:
  - Proceedings of the International Symposium on Advanced Research in Asynchronous Circuits and Systems (Async94). Salt Lake City, 1994 *(Async96 to be held in Aizu, Japan, March 1996!)*
  - A. Davis and S. Nowick, eds. *Asynchronous Digital Circuit Design*, Springer-Verlag, 1994
  - S. Hauck, Asynchronous design methodologies: An overview. *Proceedings of the IEEE*, Jan 1995
  - Asynchronous logic WWW home page http://www.cs.man.ac.uk/amulet/async/index.html