Optical Interconnections, Optical True-Time Delays, and More... All Based on the White Cell

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Introduction

- What are optical true time delays and what are they for?
- What is an optical interconnection and what's so special about OSU's?
- What is a White cell, anyway?

Organization

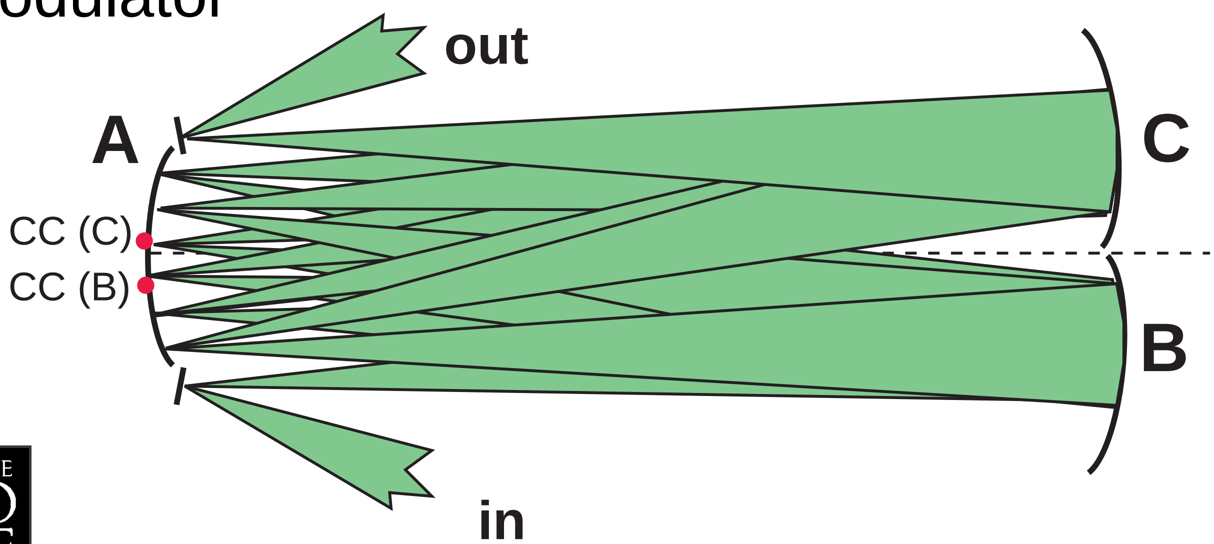
- Motivate true-time delay (TTD) work: phased array antennas
  - » What TTD is
  - » How other people do it
- Explanation of the White cell
- Adapting the White cell to TTD
- Experimental results

Organization continued

- Motivate optical interconnections (as if that’s needed)
  - » How other people do it
- Adapting the White cell to optical interconnections
- Summary and Conclusions

The White cell

- Three spherical mirrors- all identical
- Light bounces back and forth repeatedly
- Light focused to a new spot on every bounce
- We'll eventually replace Mirror A with a spatial light modulator



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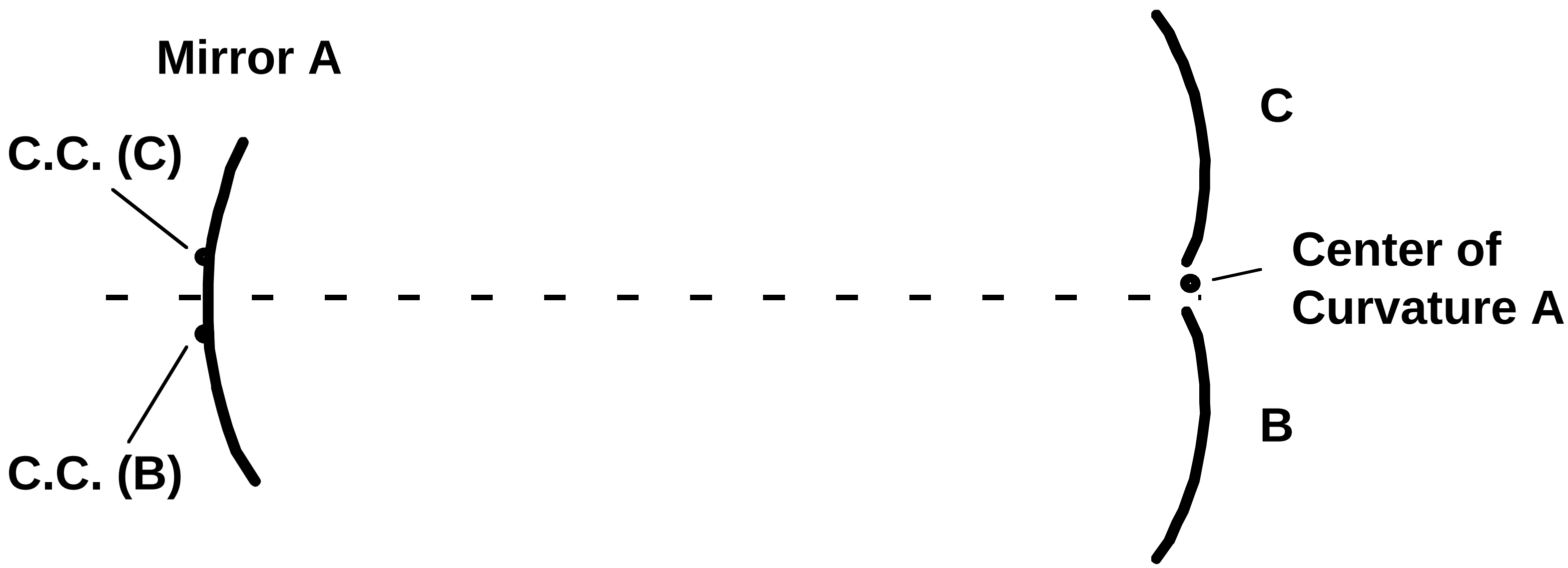
Device based on White Cell

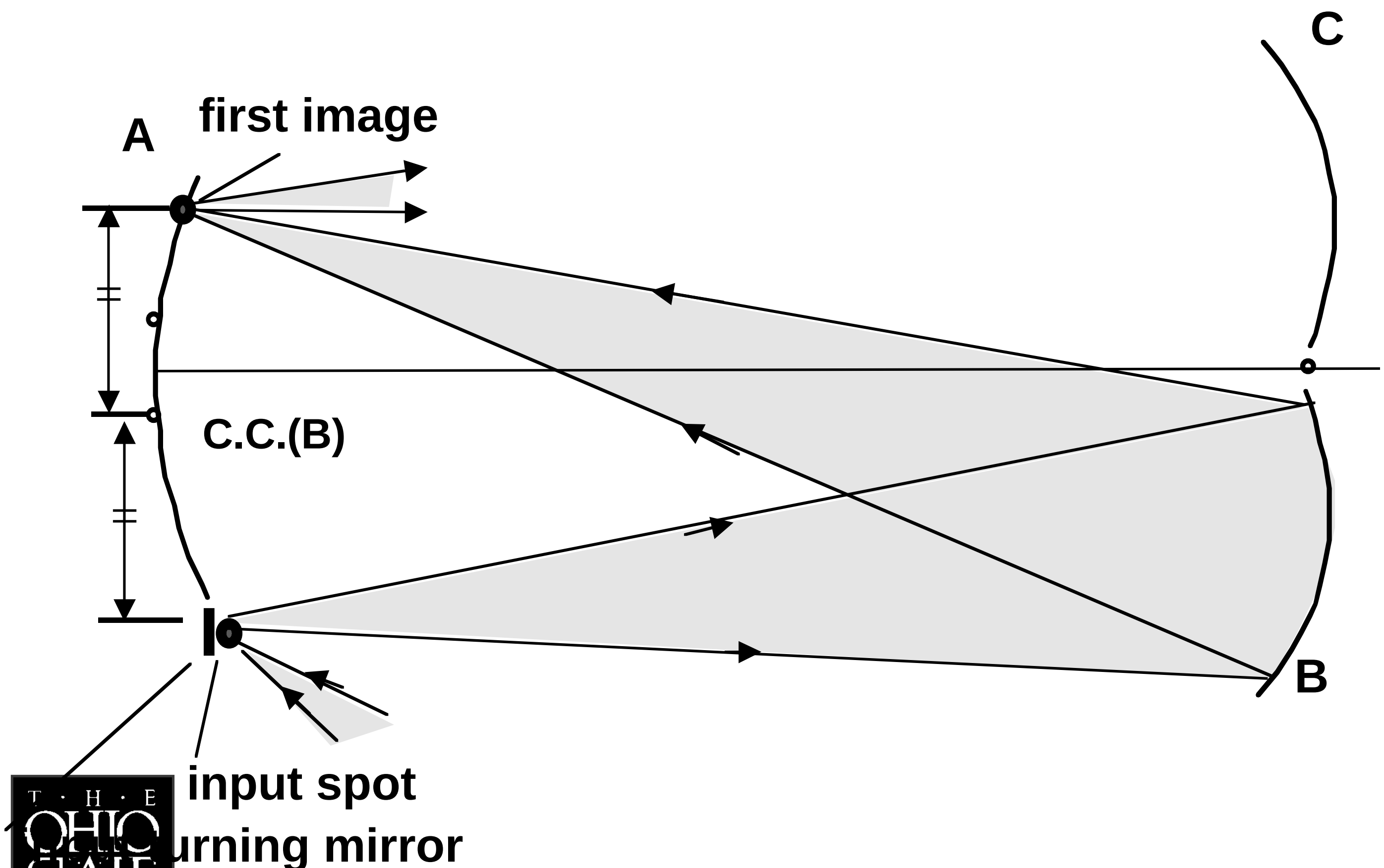
A Tale of Three Mirrors



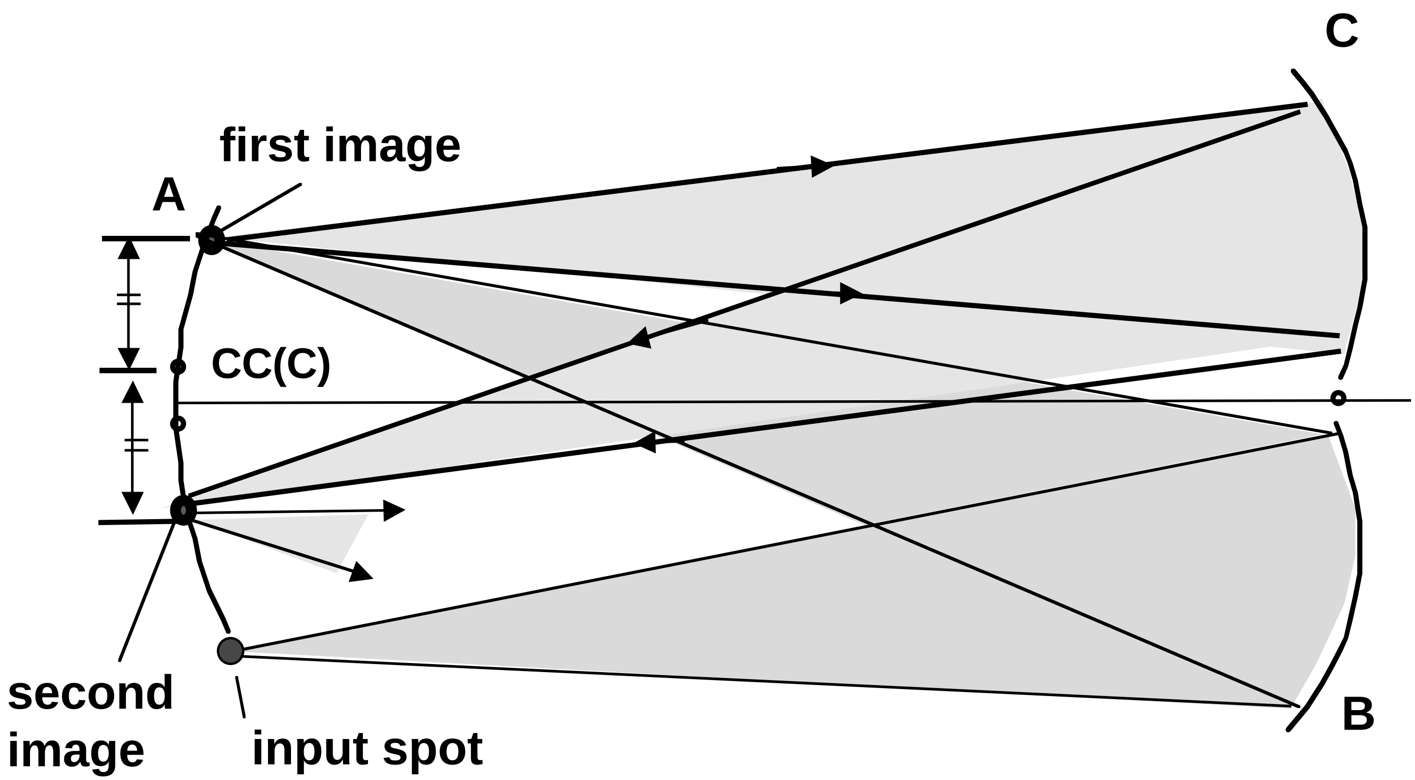
Key: mirrors refocus beam on every pass through cell

J. U. White, J. Optical Society of Am., 32,.285 (1942)

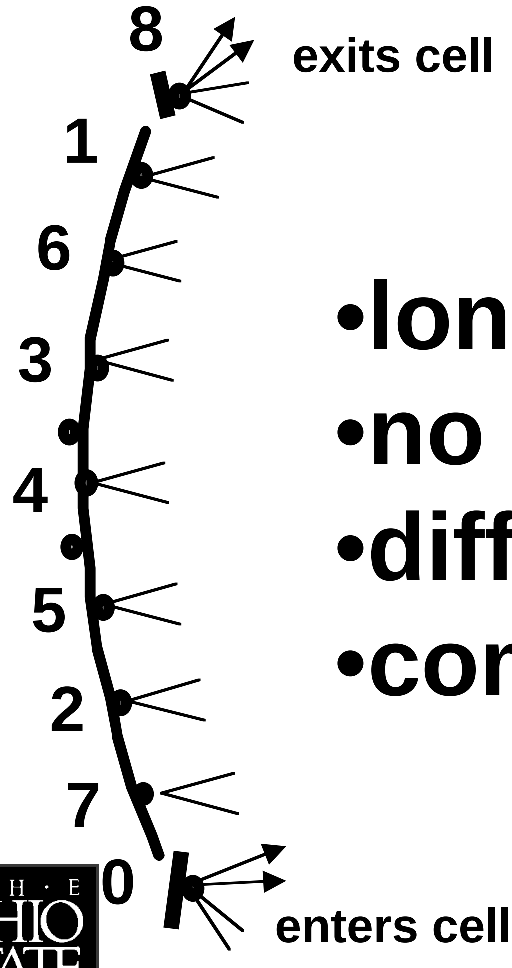
White Cell - Operation



White Cell - continued

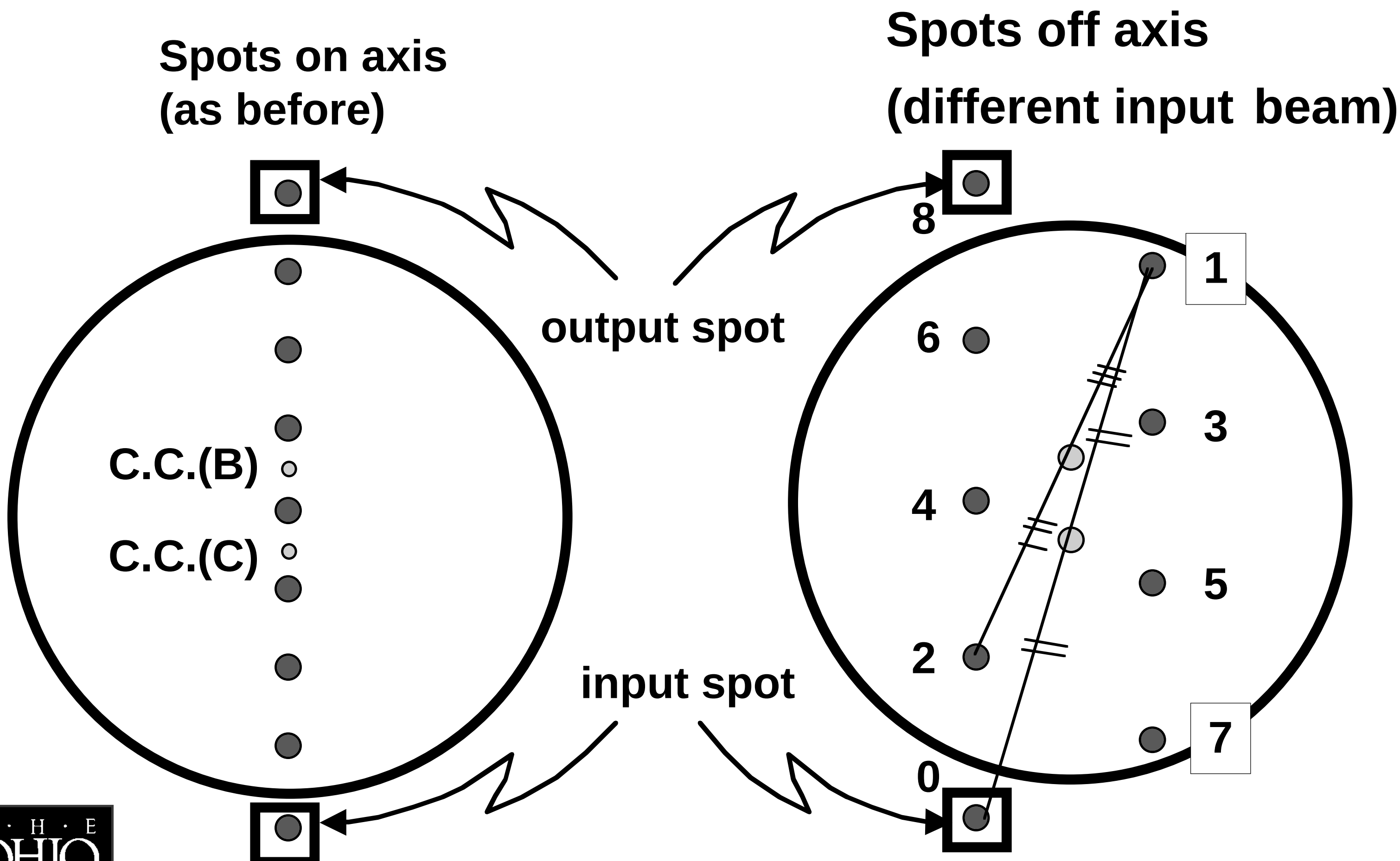


Sequence of Spot Images (for one input beam)



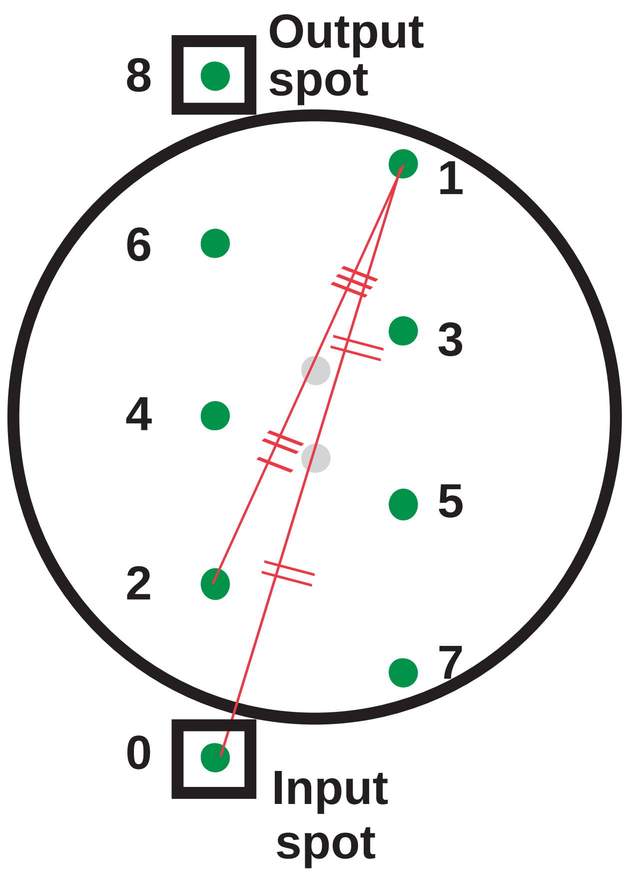
- **long optical path possible**
- **no divergence**
- **diffraction limited**
- **compact**

End View of Mirror

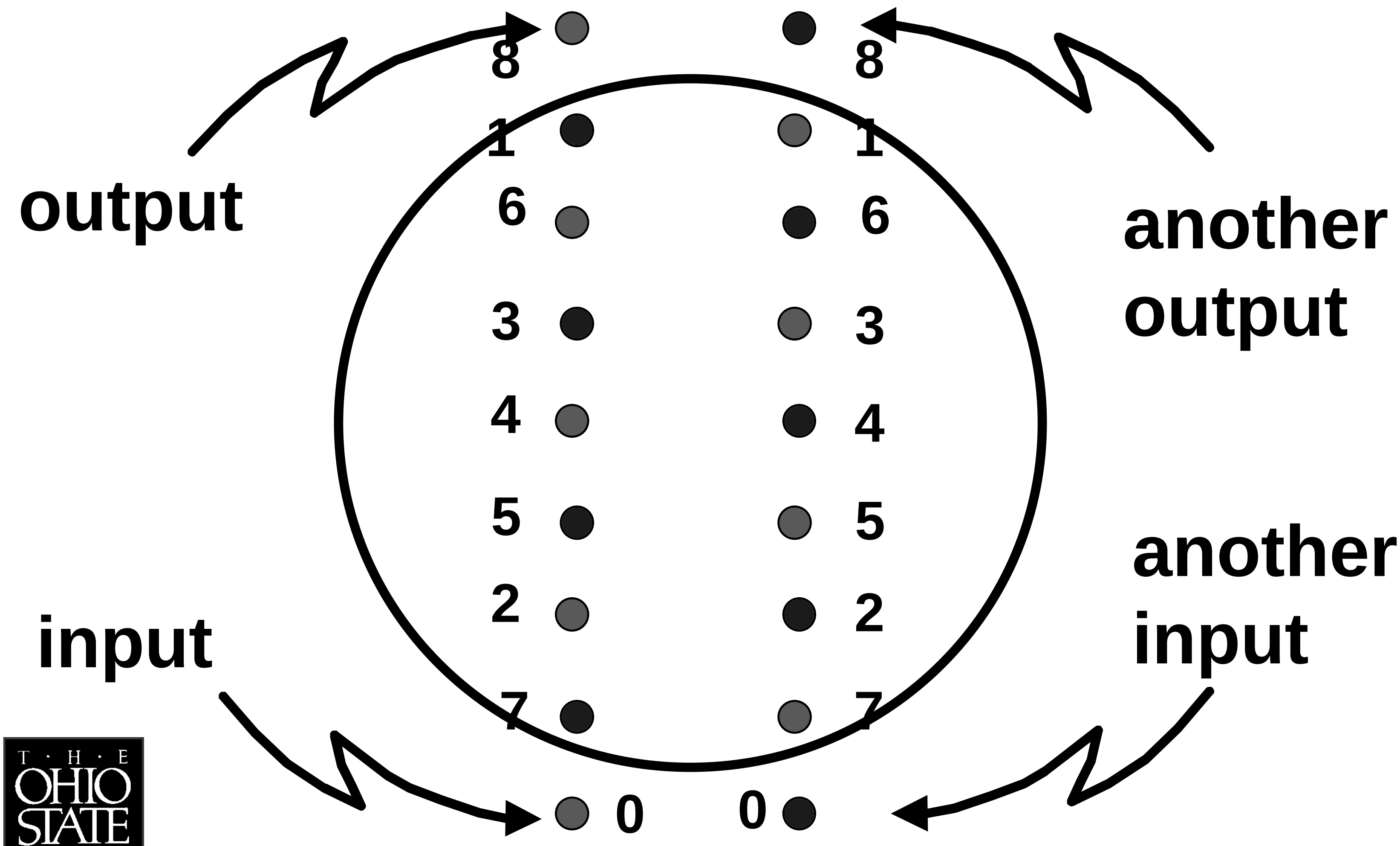


Significance of spots

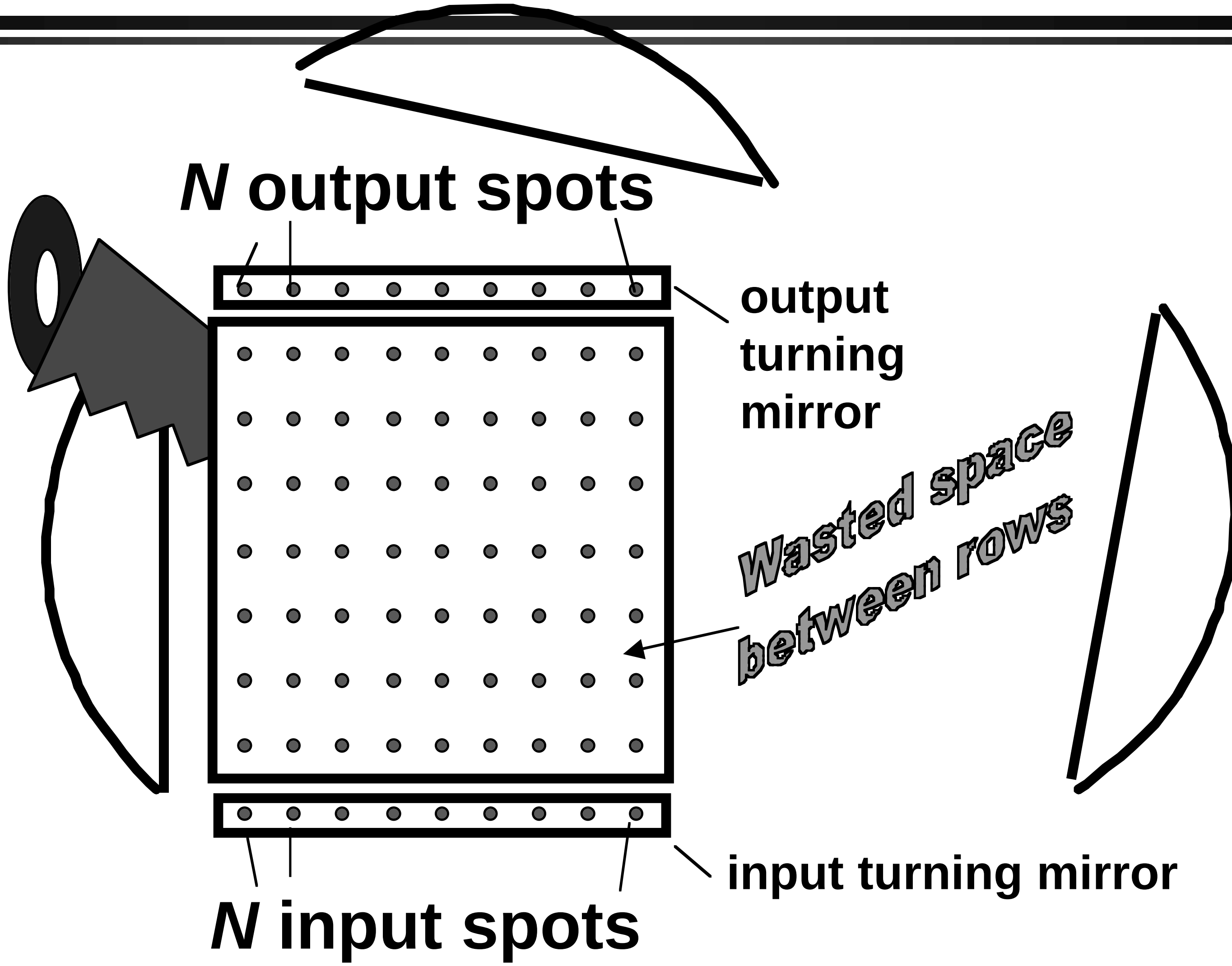
- Spot pattern depends on input location and Mirror B,C alignment
- Will map spots to pixels on SLM



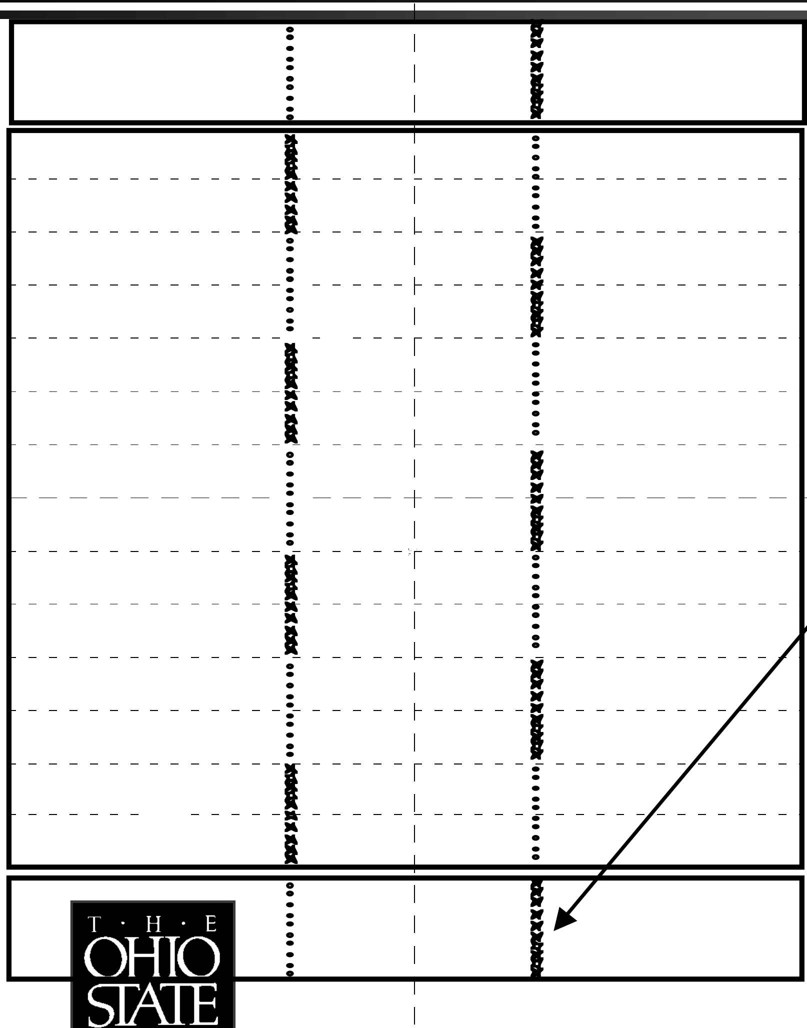
Bring in a second light beam



Complete Spot Set



Can add even more spots...



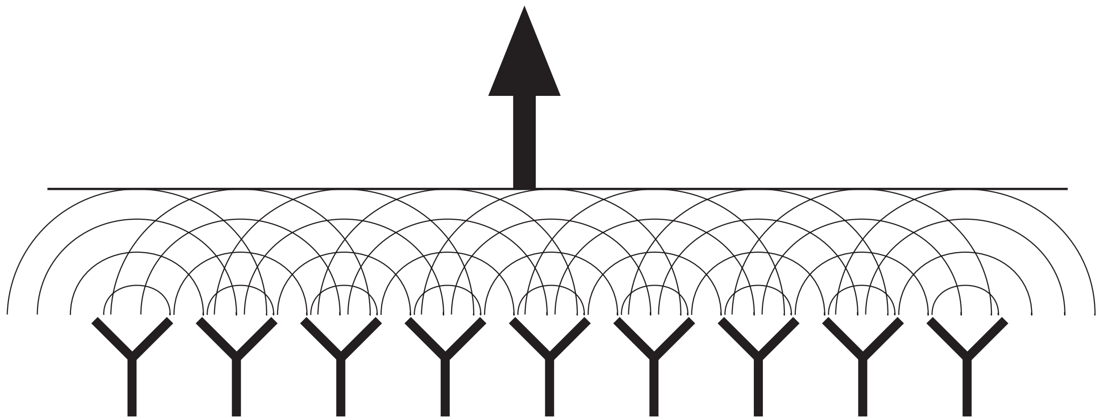
replace each input beam with a set of dots

The whole group bounces around, still striking unique pixels

Summary of White cell

- beams bounce back and forth a set number of times *m*
- *m* determined by alignment of mirrors
- many beams can circulate through cell at same time
- Now, on to the problem we want to solve…

Consider an array of antennas



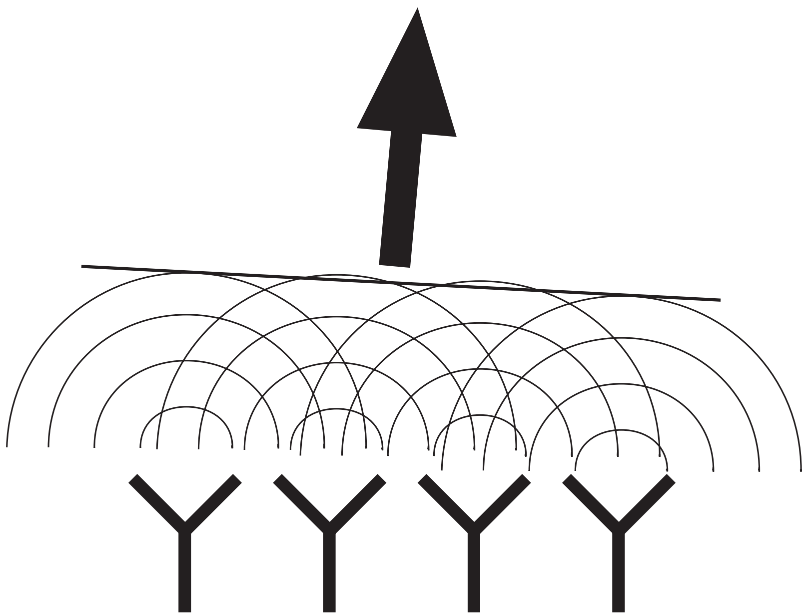
- One element alone produces a broad pattern
- Their signal add coherently to produce a highly directional beam
- Beam emitted perpendicular to the array

To steer the radar beam

- Can put the array on a stick and rotate it mechanically
  - » It’s a pain to grease the bearings if the array is on an airplane or worse a satellite
- Use phase shifting to steer the beam

Phase shifting

- In phase shifting, 2π is the same as π
- Will only get the right phase shift for one frequency
- Different frequencies go in different directions (beam squint)
- Lousy for broadband antennas



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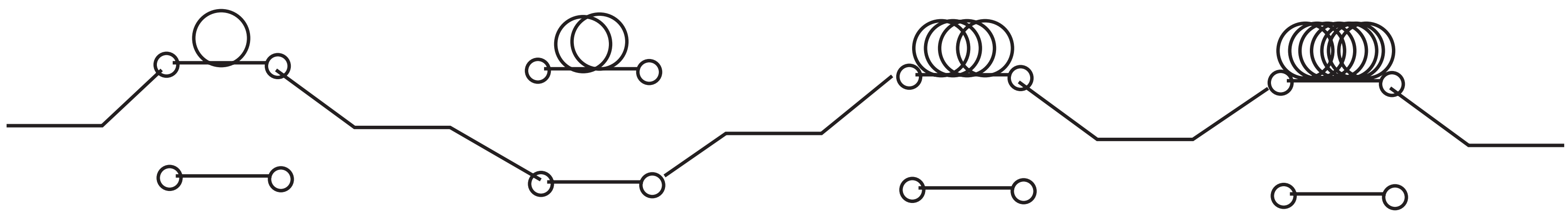
True-time delay

- A delay of 6π corresponds to some actual time
- If delay all the signals by the right times instead of phases, works at all frequencies
- Great for broadband antennas

Here's one way



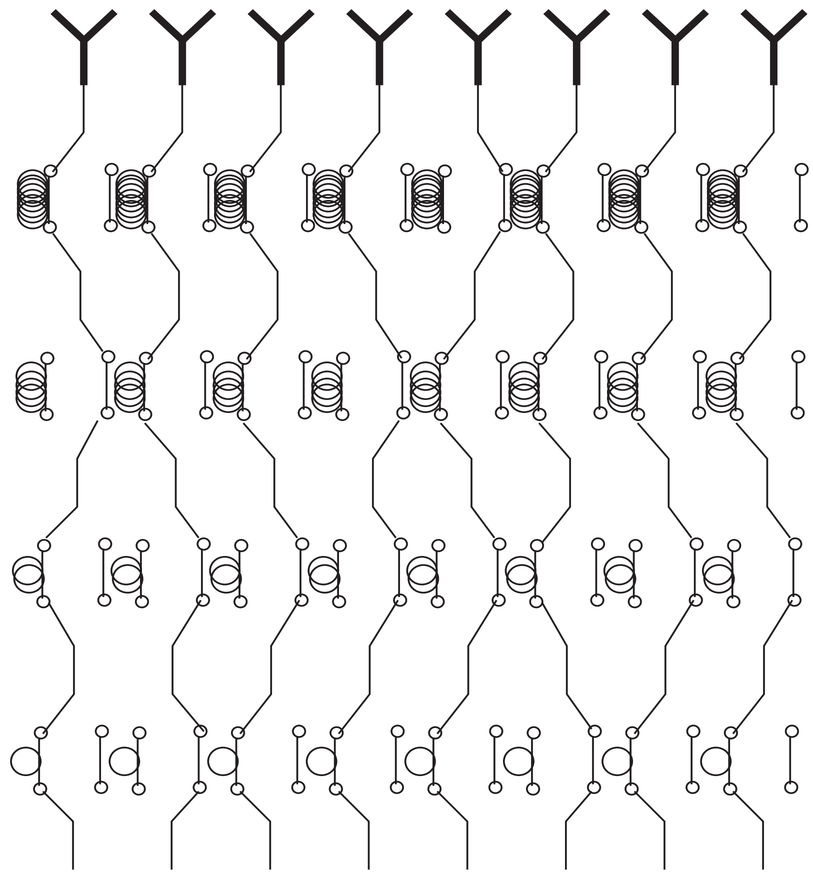
- This could be switches and lengths of coax (ech tui)
- Could be optical switches and lengths of fiber
  - » Modulate each light beam with an RF signal
  - » Delaying the light beam also delays the RF signal

There is a snag…

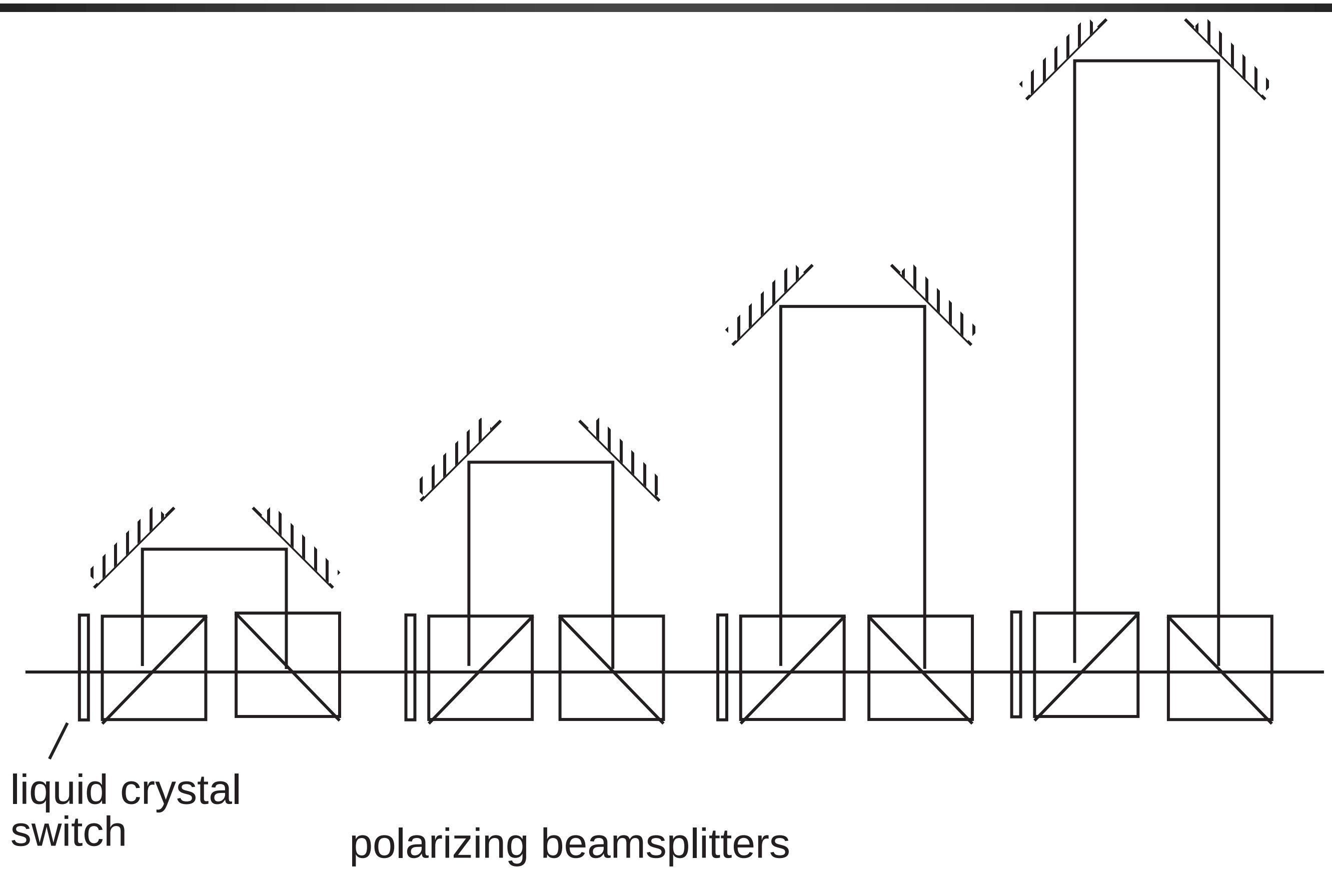
- Some delays may be as long as 100’s of ns
- That’s meters of coax or stripline
- Heavy, expensive, and temperature sensitive
- Naturally we want to do this optically…

But, need a set for every antenna element in the array

- That's a lot of hardware
- Some arrays may contain hundreds, even thousands of elements
- Ugh.



Here's a free space approach



See, for example, Riza, J. Lightwave Tech.. **12**(6), pp. 1440-1447, 1994

Features

- Free space doesn't weigh much
- Each switch can be a spatial light modulator, so can run multiple beams in parallel
- Our solution also is free space: the White cell

The White cell approach

- Adapt the White cell to time delays
- Also a free-space approach
- “Hardware compressive”
- Avoids divergence problems since beams refocused on every bounce anyway
- We’ll use liquid crystals and MEMs

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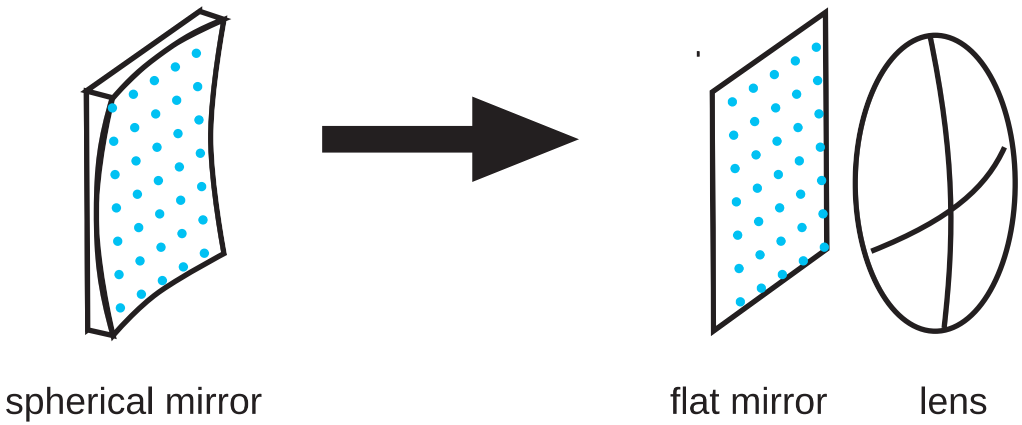
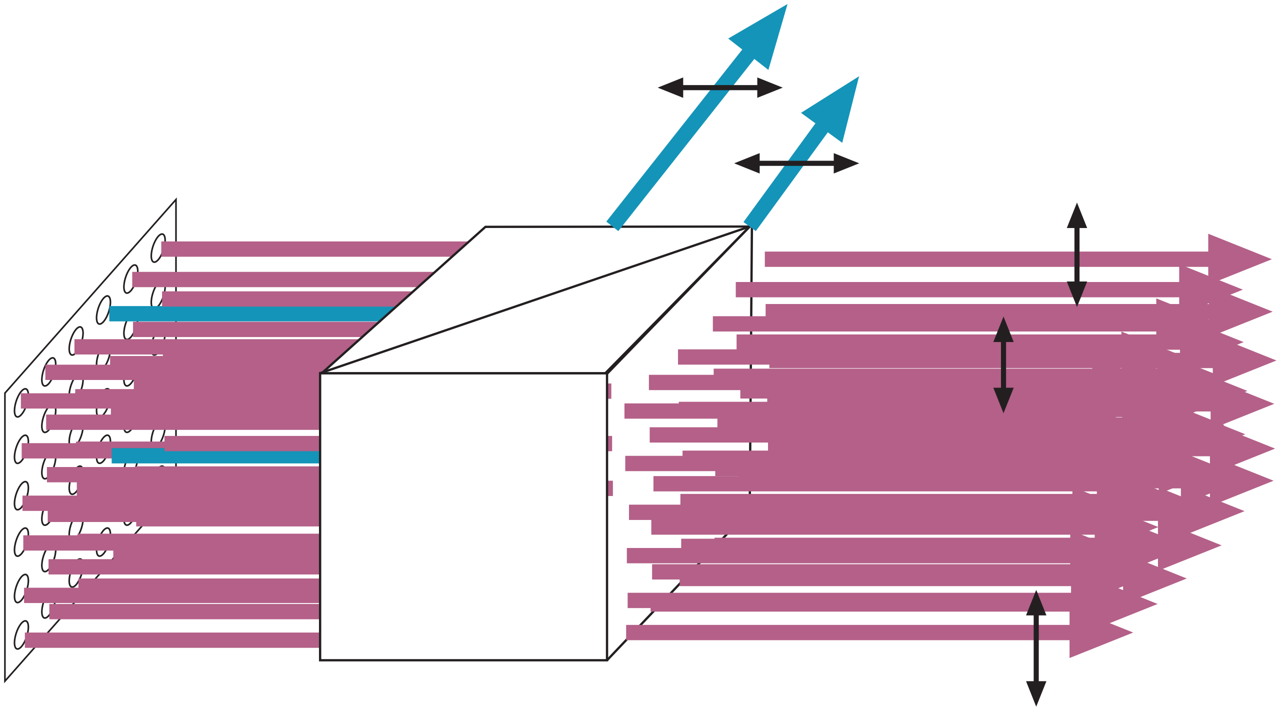
Replace Mirror A with an SLM



- Operation is the same optically
- Replace flat mirror with a spatial light modulator
- SLM can be liquid crystal or microelectromechanical device

The SLM controls the path

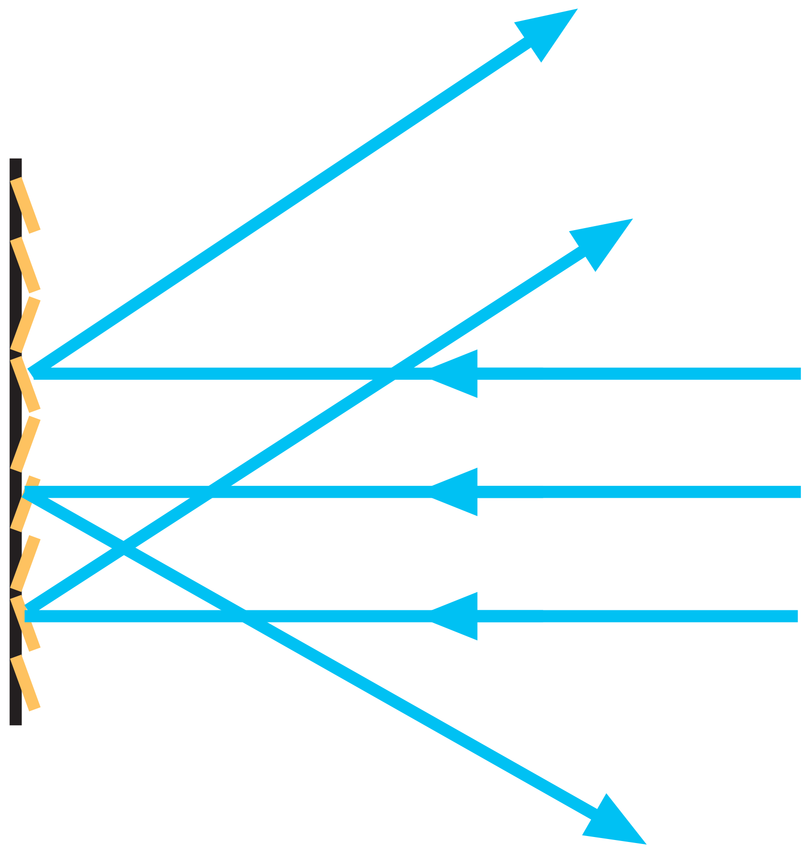


Liquid crystal-based SLM

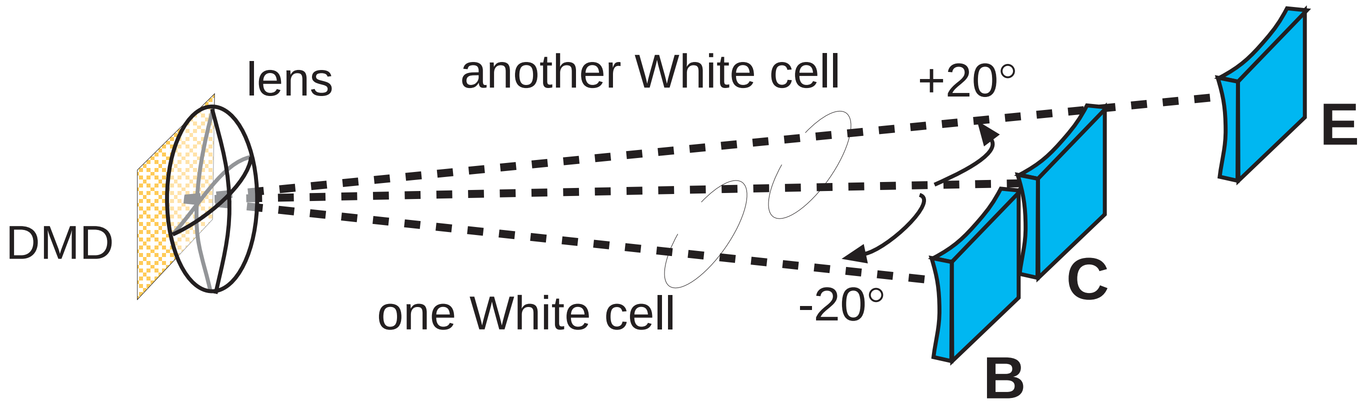
Polarizing beamsplitter

Or using a MEM

- Micromirrors tip to (in this case) two angles
- Beams are deflected in either of two directions
- Put this into a White cell



Replace Mirror A with MEM and lens



- Let MEM be TI DMD
- Can form two White cells
- Path length different for White cells but spot pattern is the same regardless of path

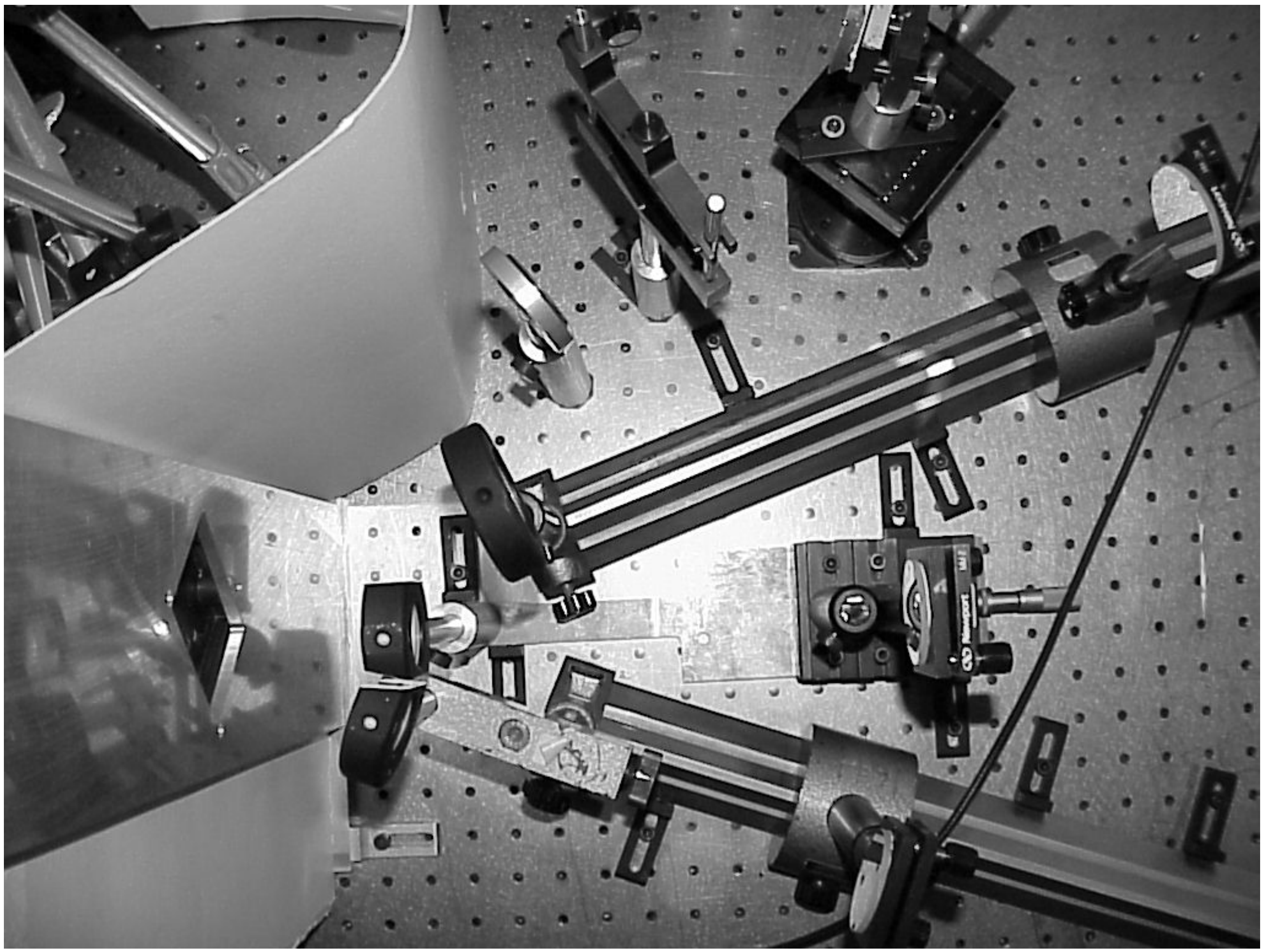
We call this a linear TTD cell

- Number of delays is proportional to *m:*

$$N = \frac{m}{2}$$

- where *m* is the number of bounces
- Note number of bounces is fixed- set by spherical mirrors

Linear cell apparatus



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We built it

- Time increment was 1 ns
- Used pulsed laser (green) to measure delays
- Loss ≈ 1.2 dB/bounce
  - » Diffraction a big problem
    - – Pixels smaller (16 μm) than our beam
    - – We used a 50x50 pixel “macropixel”
    - – Get diffraction off interpixel gaps and holes in mirrors
  - » Mirrors are aluminum (gold has higher reflectivity)

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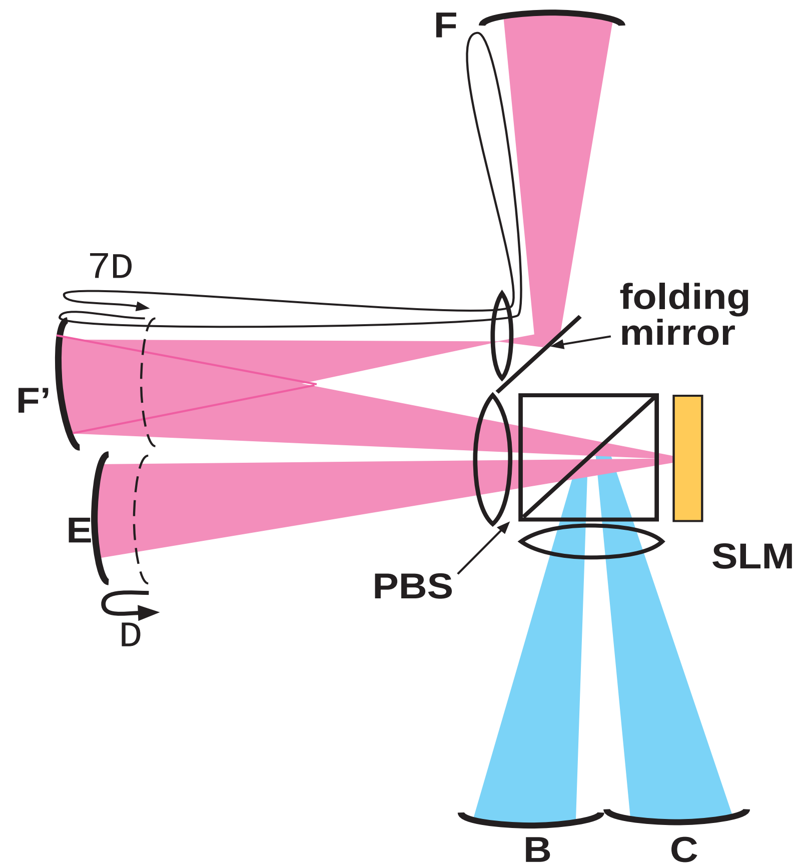
Next design (using an LC)

- “E” is the one’s place
- Can count up to *m/2* by going to E (say, 6 in 12 bounces)
- Make “F” longer by 1 (the 7’s place)
- Can go there up to six times



This is a quadratic cell

- Number of delays goes as

$$N = \left(\frac{m}{2}\right)\left(\frac{m}{2}+1\right)+\left(\frac{m}{2}\right)=\left(\frac{m}{2}\right)^2+2\left(\frac{m}{2}\right)$$

- Quadratic in *m/2*

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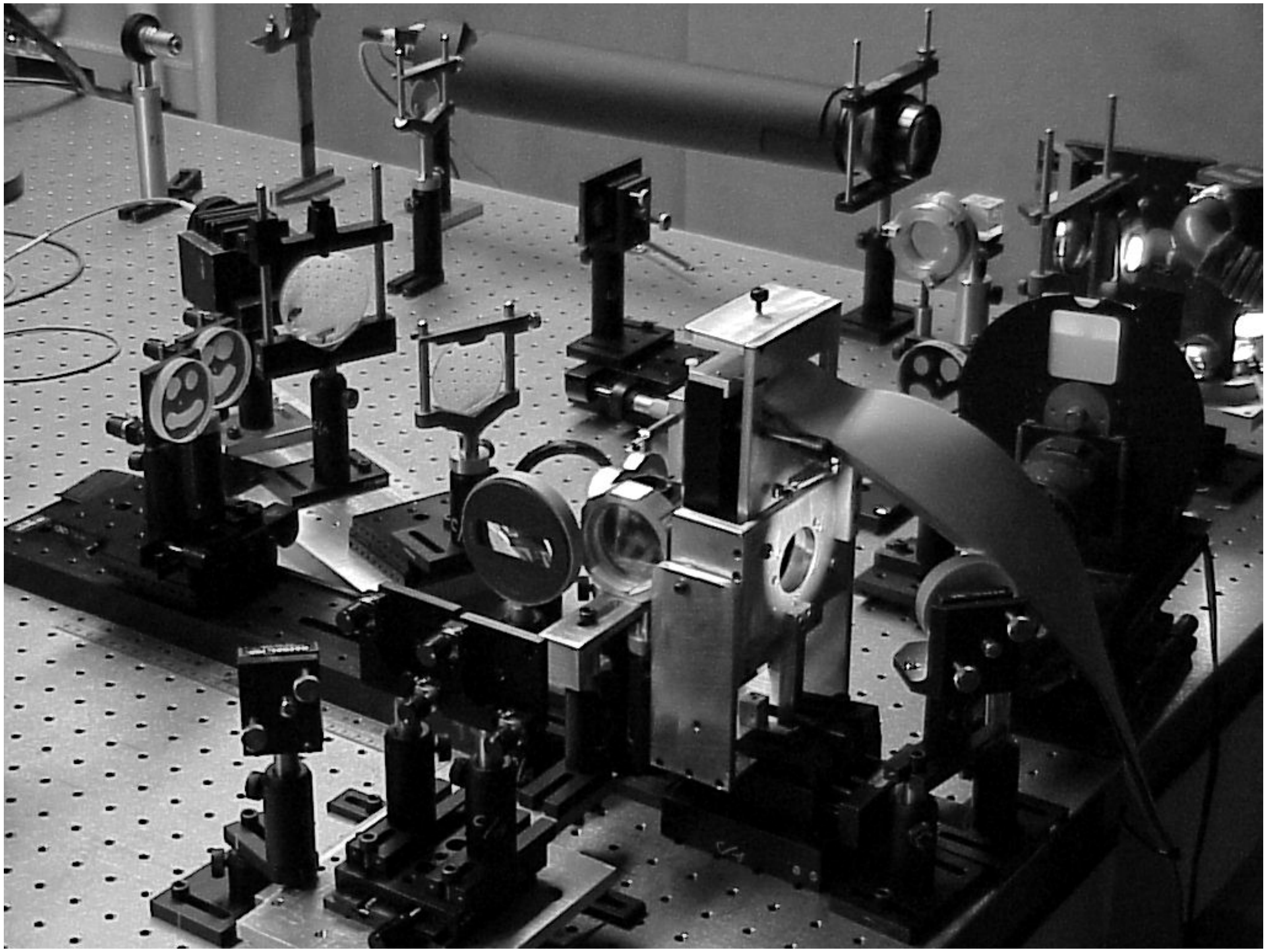
Quadratic cell apparatus



We built it

- Used Nd:YAG laser (1319 nm)
- Time delay increment 1 ns
- Had four input spots
  - » Fiber array in silicon V-groove
- Losses about 1 dB/bounce
- Crosstalk was lousy (we didn’t specify SLM correctly)

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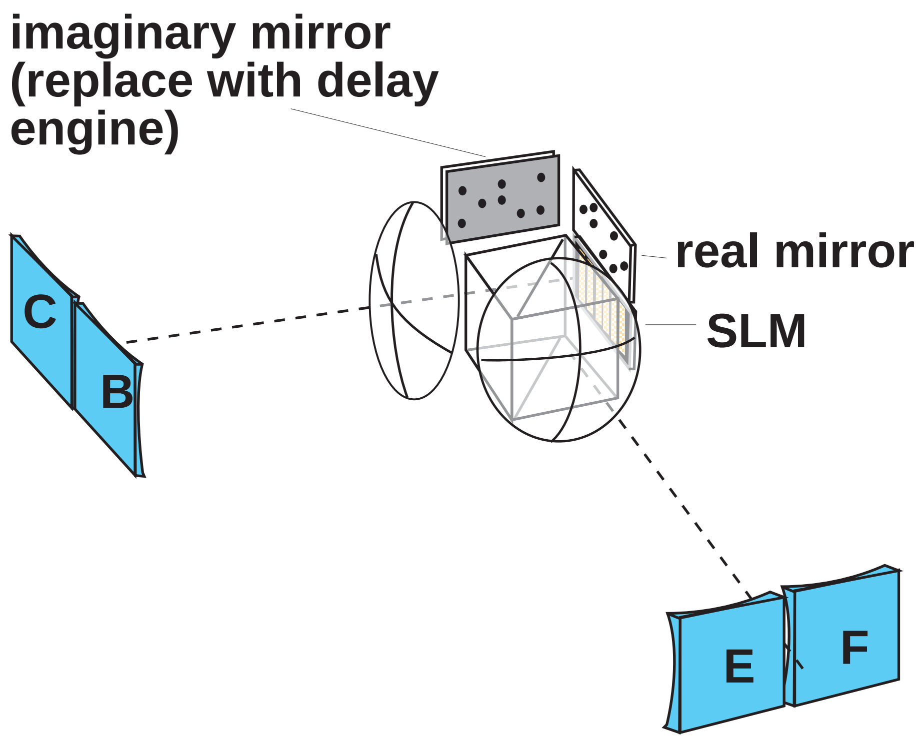
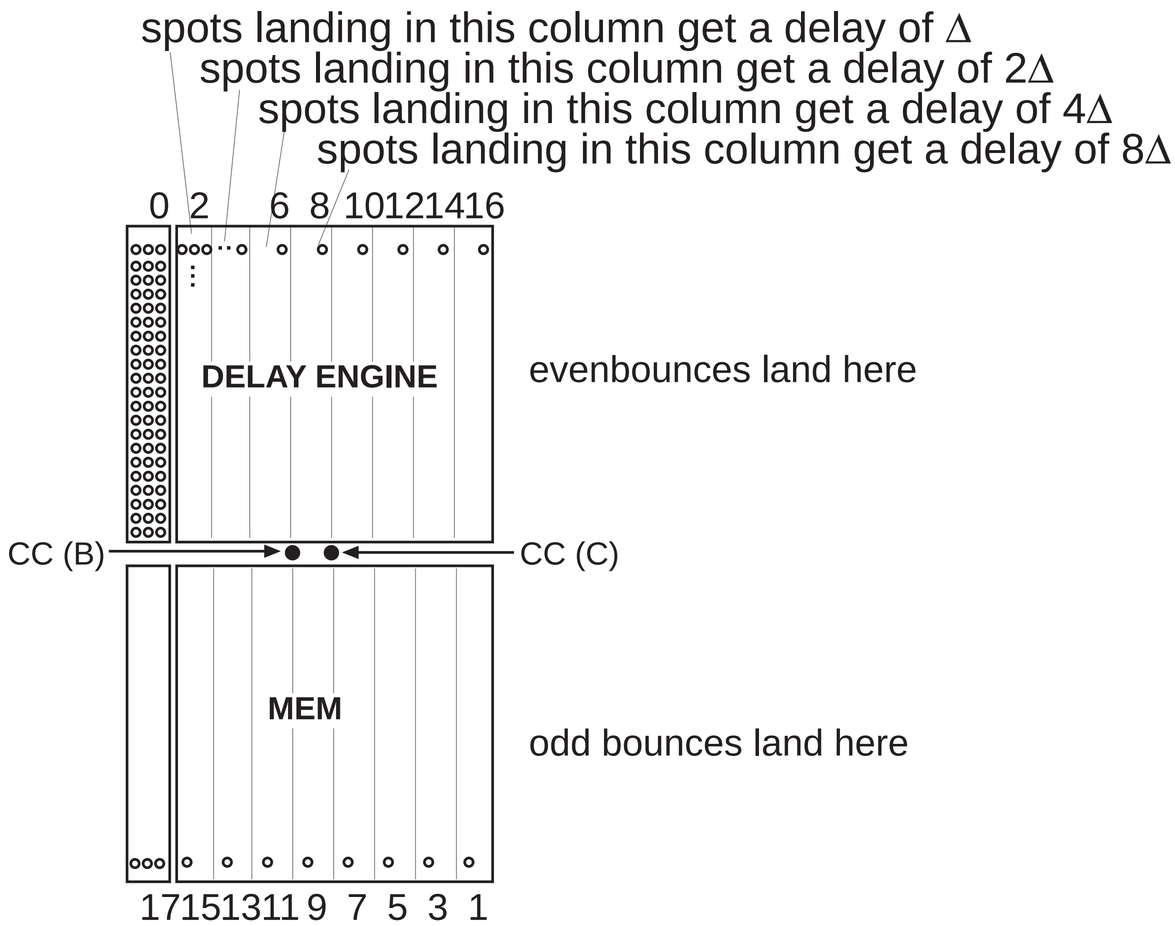
Want more delays

- New architecture: re-image spots from SLM onto a delay engine
- Each column of spots has a delay twice that of previous column
- For no delay that bit, go to a plain mirror

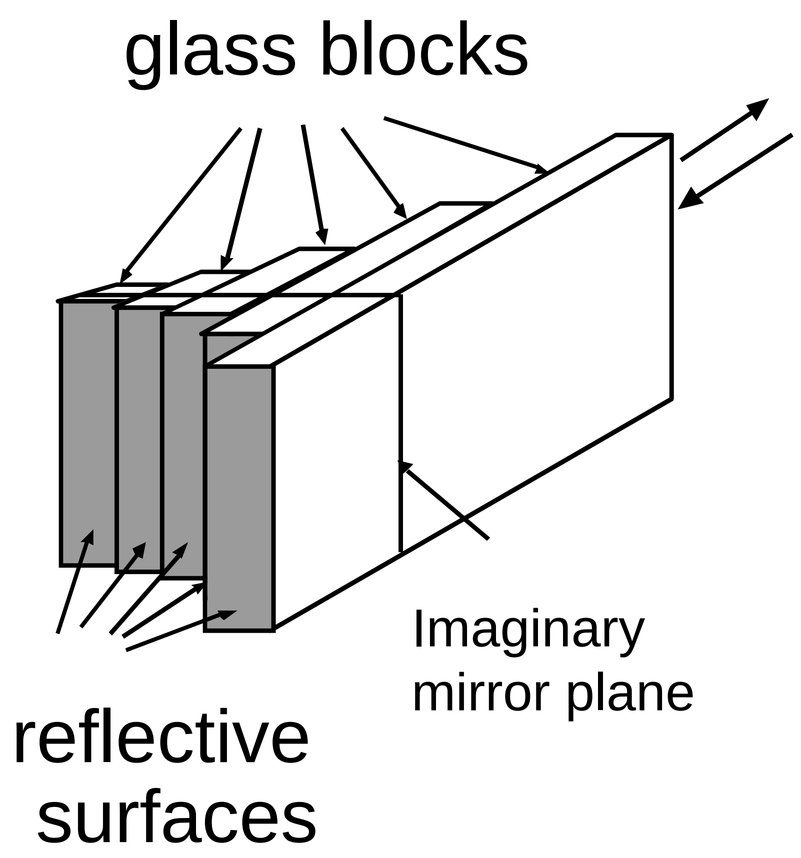


Assignment of columns



Example of delay engine

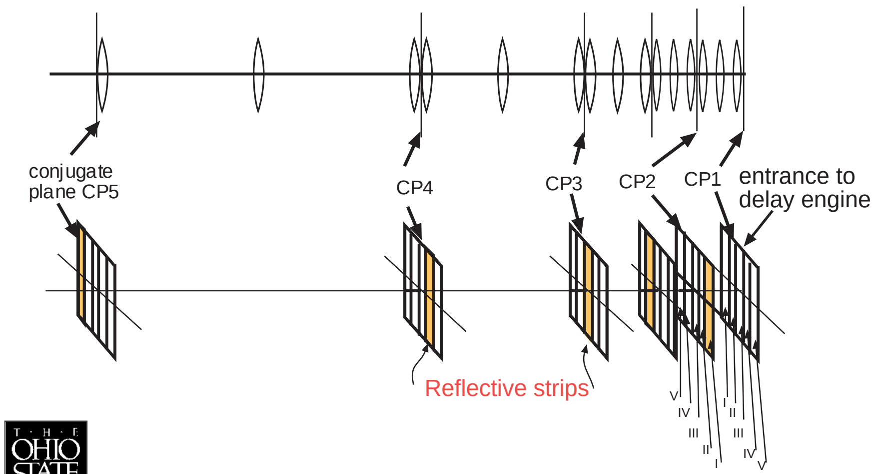
- Glass slows light
- Images at different plane so longer path
- Each block twice the length of previous one
- Good only for short delays

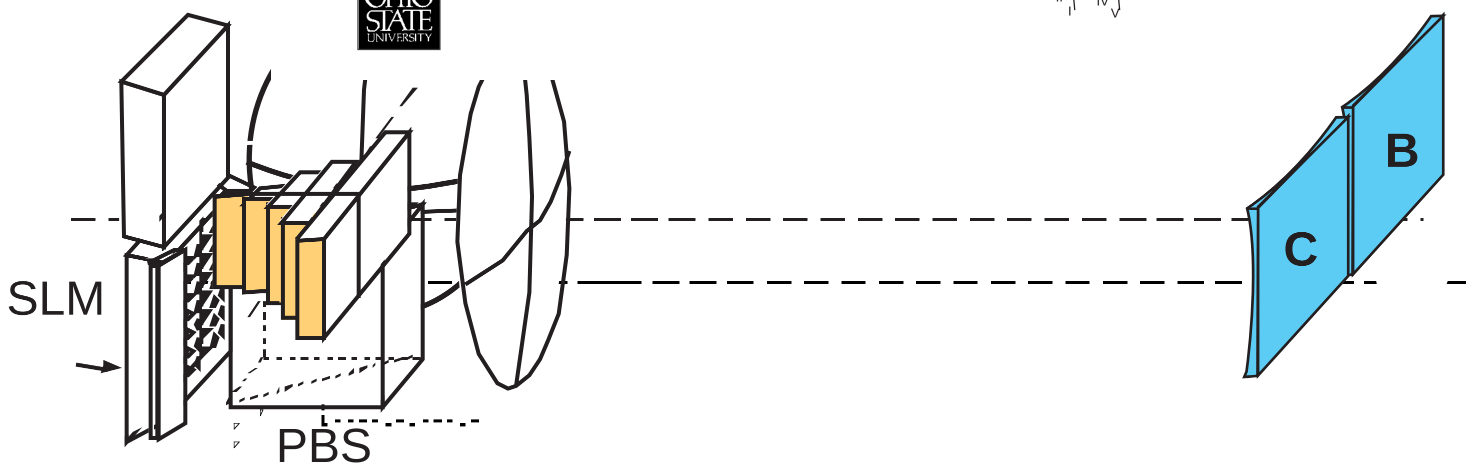


For longer delays: lens train

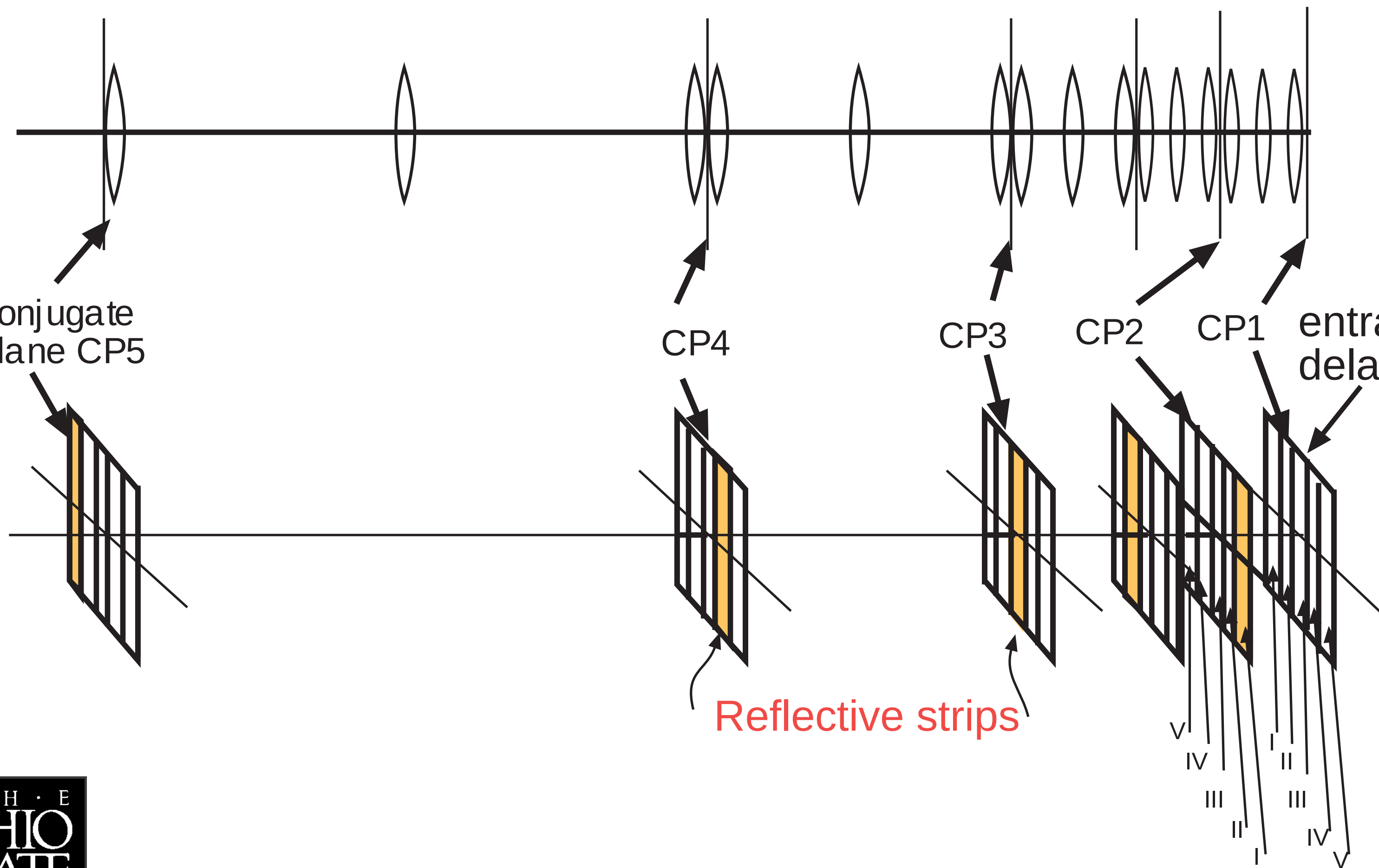
Put

m





For longer delays: lens train



We’re building that

- Liquid crystal SLM
- 1319 nm light
- 7 bits in glass blocks (1 ps up to 128 ps)
- 6 bits in lens train (512 ps up to 16.4 ns)

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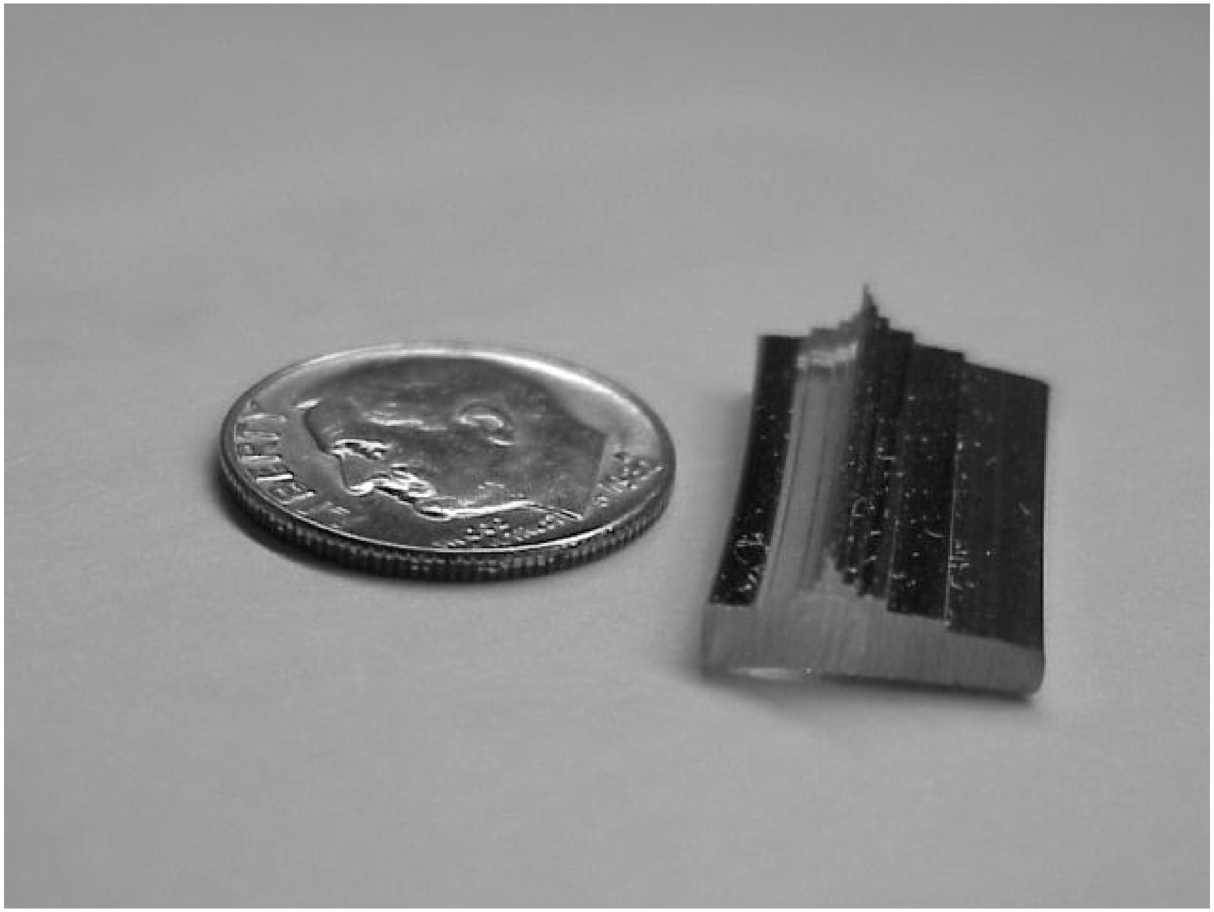
Glass block results

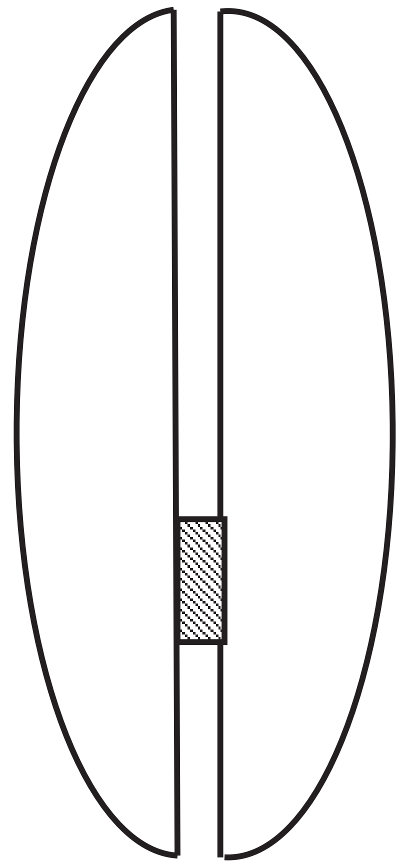
- Used PMMA (faster, cheaper)
- Vendor unable to make without twisting, warping
- Have not put resulting transporter accident into system yet

The outcome

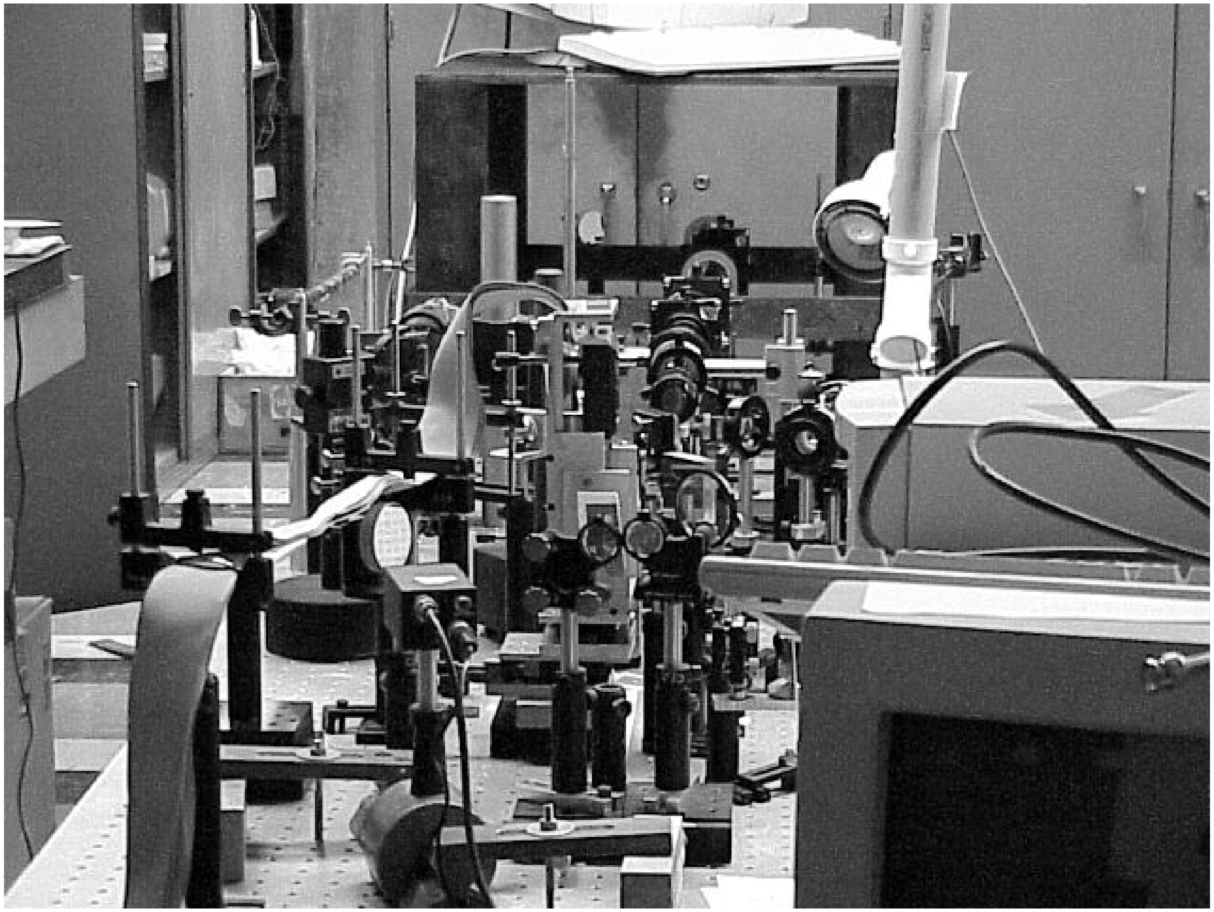


Lens train

- 6 bits means 18 lenses
- Implementation of strip mirrors clever but made alignment darned hard
  - » Have to offset, tilt mirror just right, but lens goes with it
  - » Ultimately had to separate them (drat)



The apparatus



Lens Train

- Got it all aligned at visible
  - » Image SLM to every mirror plane
  - » Image every field lens onto every other
- Now re-aligning at infrared
- No data yet

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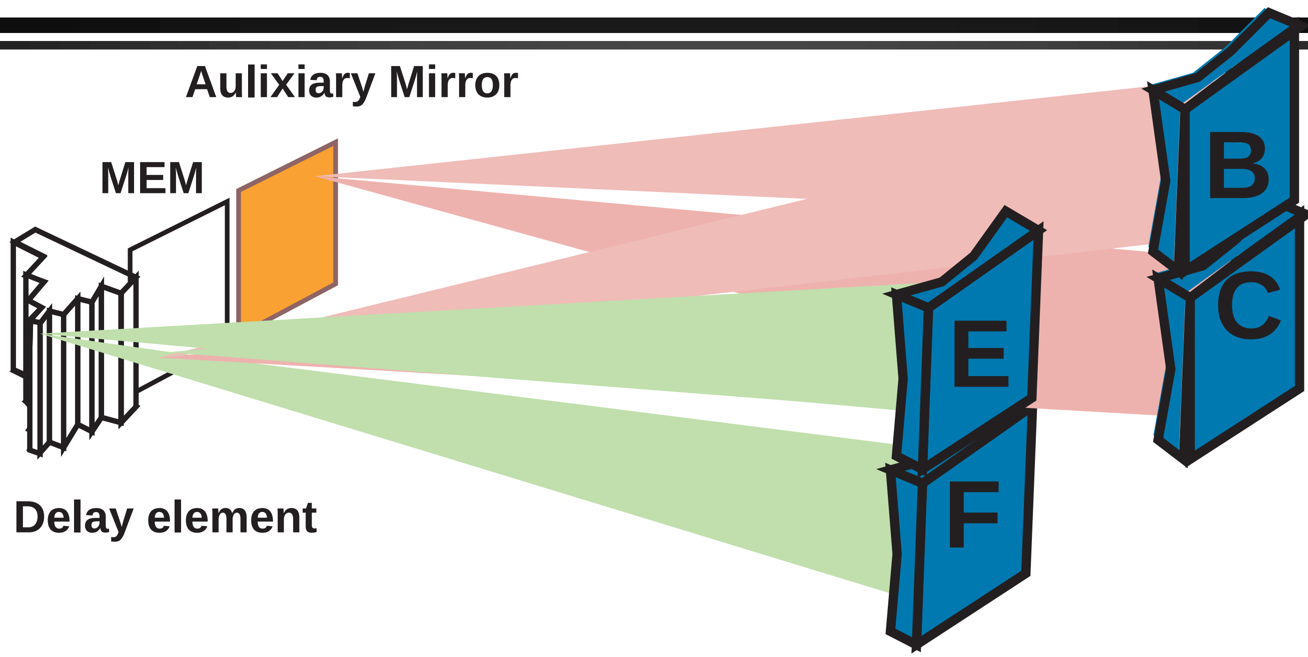
But we’re still looking ahead

- Next: present some designs for higher order cells
- Two flavors:
  - » Polynomial (like quadratic), where $N \propto m^x$
  - » Exponential (like binary) where $N \propto x^m$
- New designs use MEM’s

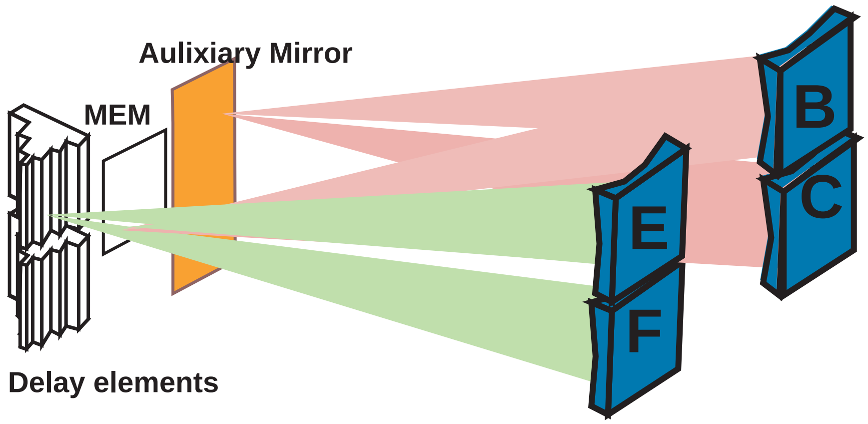
Binary cell with MEM



- In any two bounces, can visit delays or null path

$$N = 2^{\frac{m}{2}}$$

Can do better



- Two delay elements
- First: Columns delay by $\Delta, 3\Delta, 9\Delta...$
- Second: Columns delay by $2\Delta, 6\Delta, 18\Delta...$

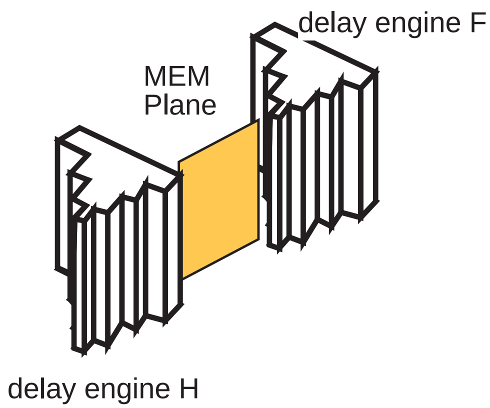
“Ternary” cell

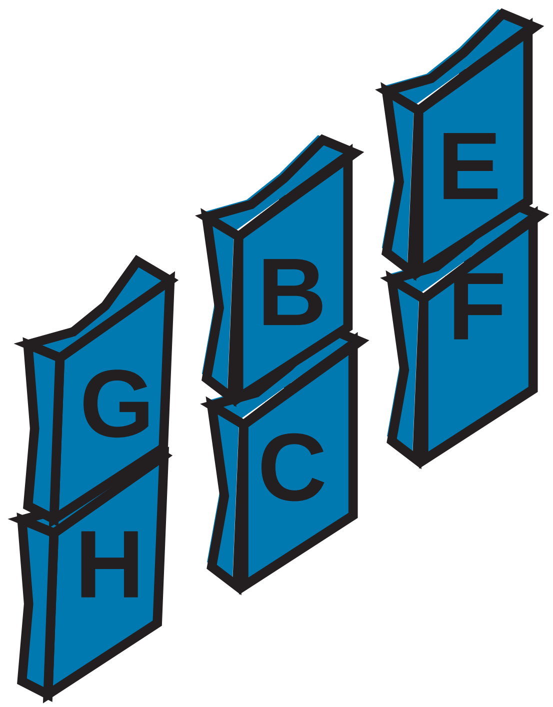
$$N = 3^{\frac{m}{3}}$$

But, suppose a MEM had three states

- TI DMD can tilt to ±10°
- “Flat” position not stable
- But, if it were, could have more choices of paths on every bounce

So, with three-state MEM



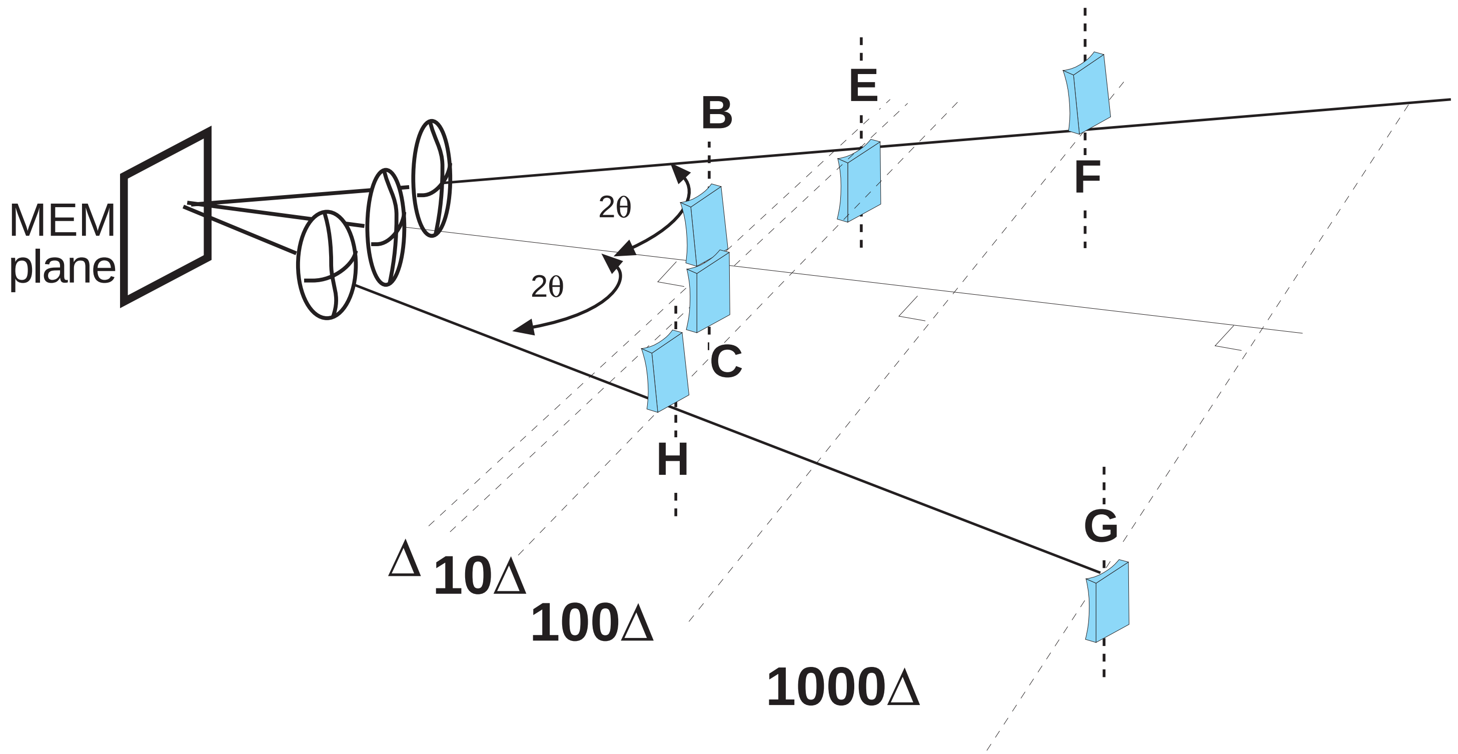


Assignment of columns…

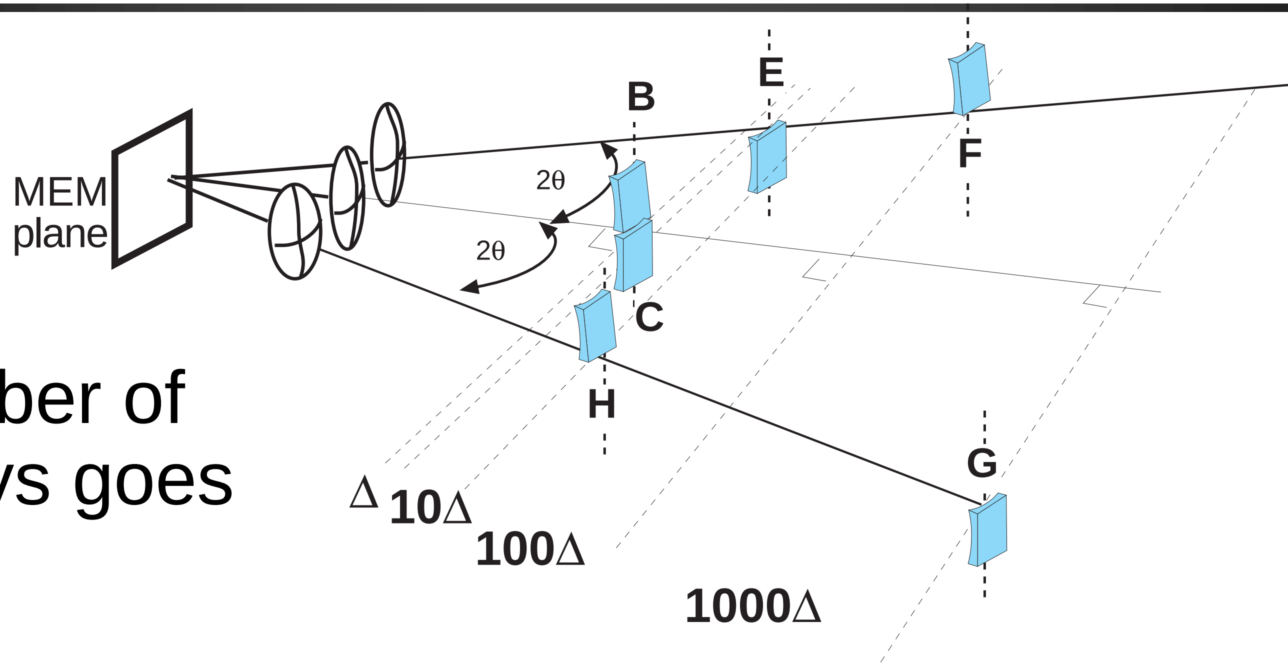
	Column 1	Column 2	Column 3	Column *m*
Delay Element E	1Δ	4Δ	16Δ	$4^{\left(\frac{m}{2}-1\right)}\Delta$
Delay Element G	2Δ	8Δ	32Δ	$2\times 4^{\left(\frac{m}{2}-1\right)}\Delta$

$$N = 4^{\frac{m}{2}}\Delta$$

Can do higher order polynomial cells, too



This is a quartic cell



- Number of delays goes as

$$N = \left(\frac{m-2}{4}\right)^4 + 4\left(\frac{m-2}{4}\right)^3 + 6\left(\frac{m-2}{4}\right)^2 + 4\left(\frac{m-2}{4}\right) - 1$$

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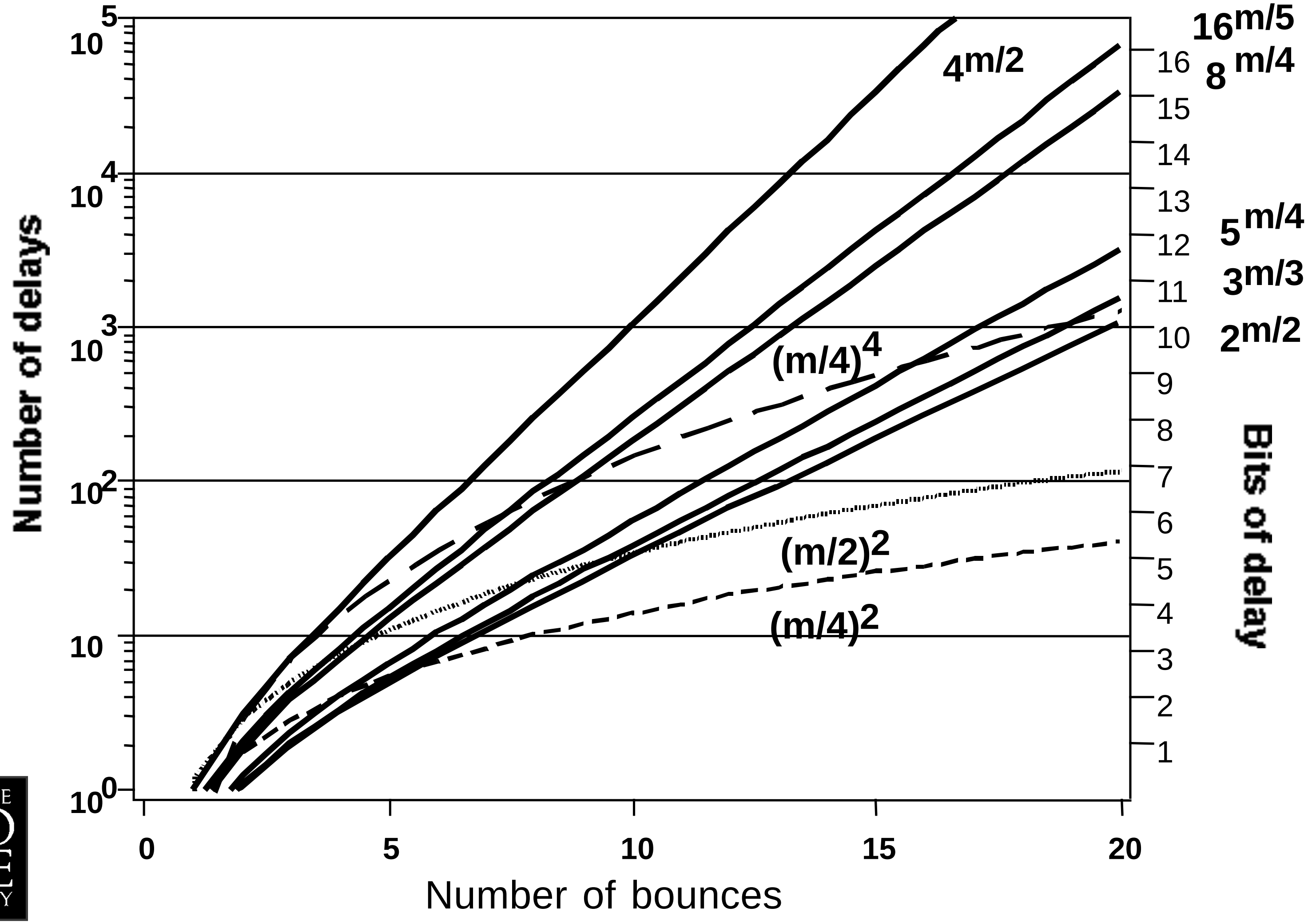
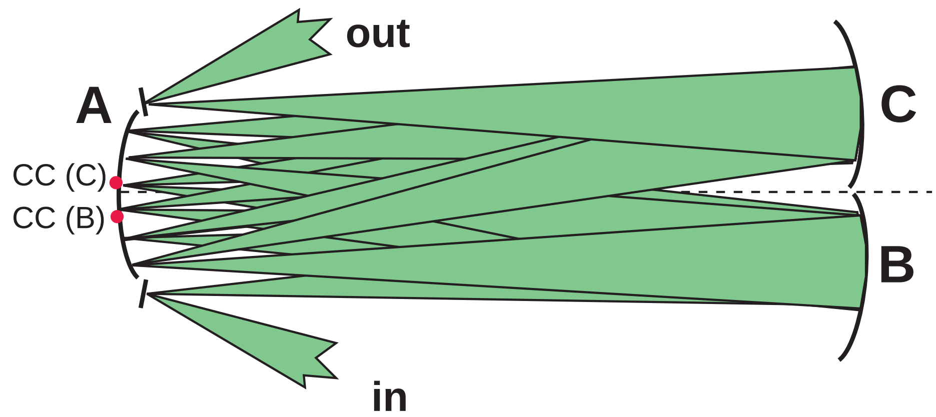
Comparison of devices



Summary of key points



- White cell has multiple bounce scheme
- Refocus each beam to spots on SLM pixels
- Can switch a beam on any bounce

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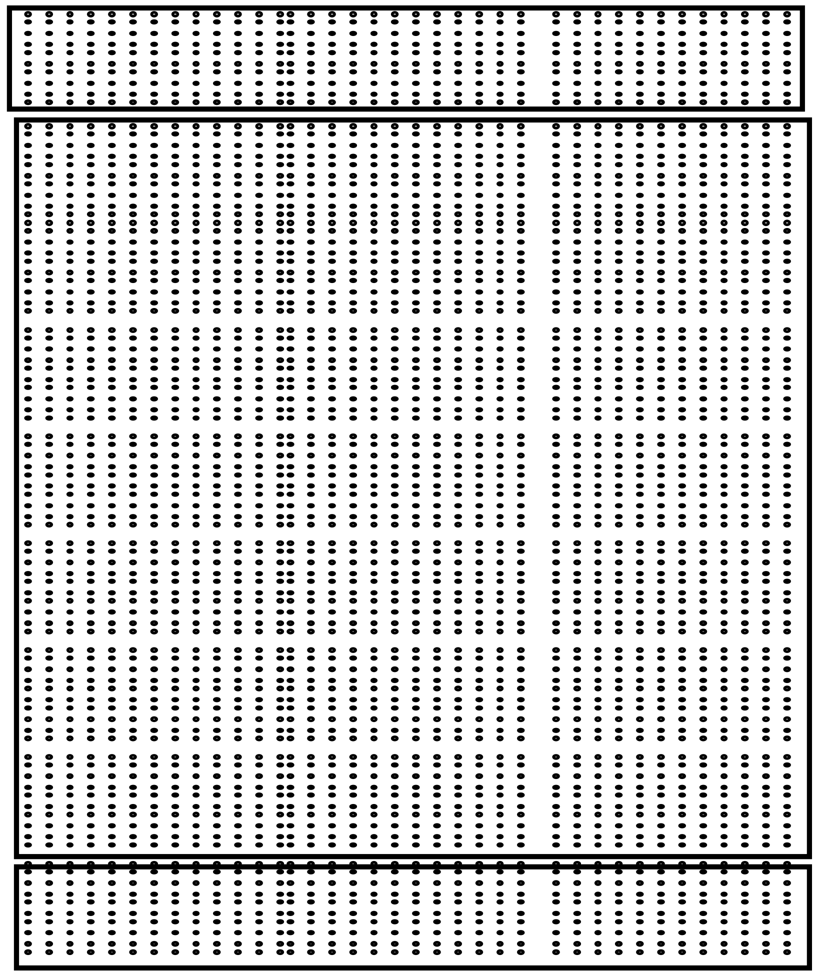
White cell can support many beams

- One input spot for each antenna element
- Can support large phased arrays with one spatial light modulator



Got to keep *m* down

- Lots of loss each bounce (≈1dB with current SLM's)
  - » Almost all of loss due to SLM, not other components
  - » Need MEM's with gold mirrors
- Need to get a lot of delays for small number of bounces
- Led us to various designs

Advantages and disadvantages

- Polynomial cells
  - » Loss independent of delay
  - » Fewer components to align
  - » OK number of delays
  - » May make more delays for small number of bounces
- Exponential cells
  - » Loss varies slightly with delay
  - » More complex hardware-wise
  - » Can get a boatload of delays with a lot of bounces