An Optical Turing Machine for Network Processing

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OTM Overview

- High-speed communication is multibit optical
  - Computation pace needs multibit optical
  - Shared encoding suggests unification
- USC/ISI's OTM initiative
  - Revisits the assumptions of computation
  - Leverages native optical capabilities

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Current Optical Computing

- Analog signal processing
  - Spatial Fourier transforms (lens/lens-like)
  - Holography
  - RF-like wave manipulation
- Emerging digital approaches
  - Optical transistors
    (D. Miller, *Nature Photonics* 2010)
  - Quantum dots

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What's missing?

- Analog processing limits
  - Implements static functions
    - Want Turing-complete reconfigurability
  - Limited composition
    - Want arbitrarily long sequences of functions
- Emerging digital approach limits
  - Optical transistor and quantum dots have low bandwidth
    - Still one bit per device

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What is an
Optical Turing Machine?

- A USC/ISI initiative to create:
  - A new approach to computing
    - Optical computing…
    - of high-density (multibit) symbols
      which natively support
      high-speed, long-distance transmission
  - A fundamental unification
    - Integrate computation and communication
    - from the communications viewpoint

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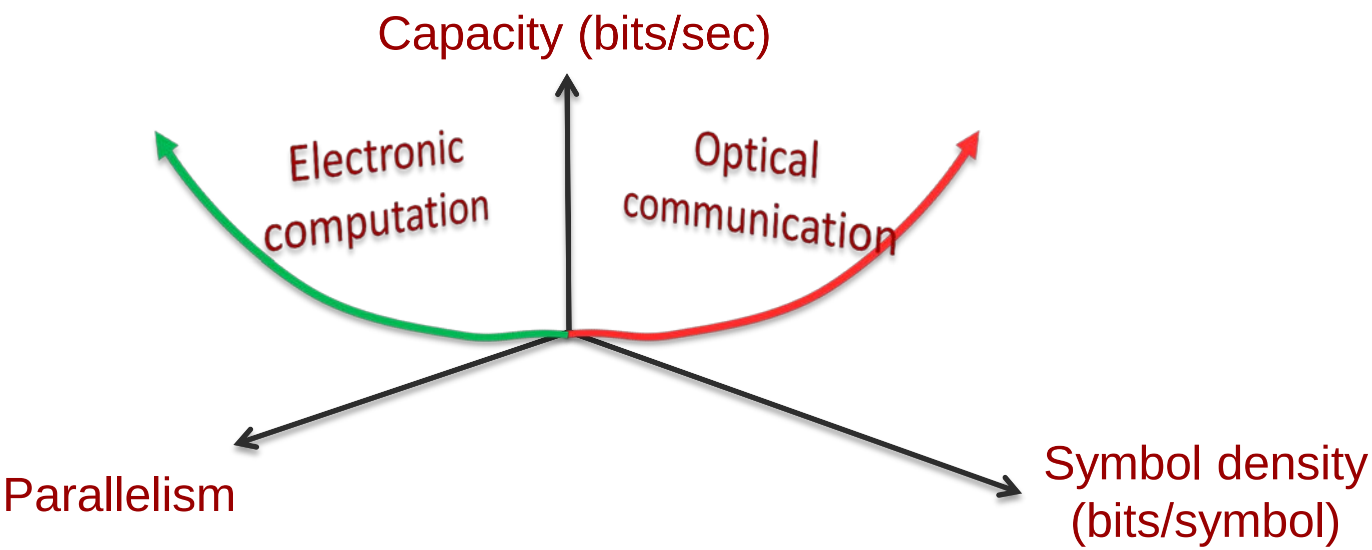
Diverging approaches to high speed

- Computation increases parallelism
- Communication increases bit density



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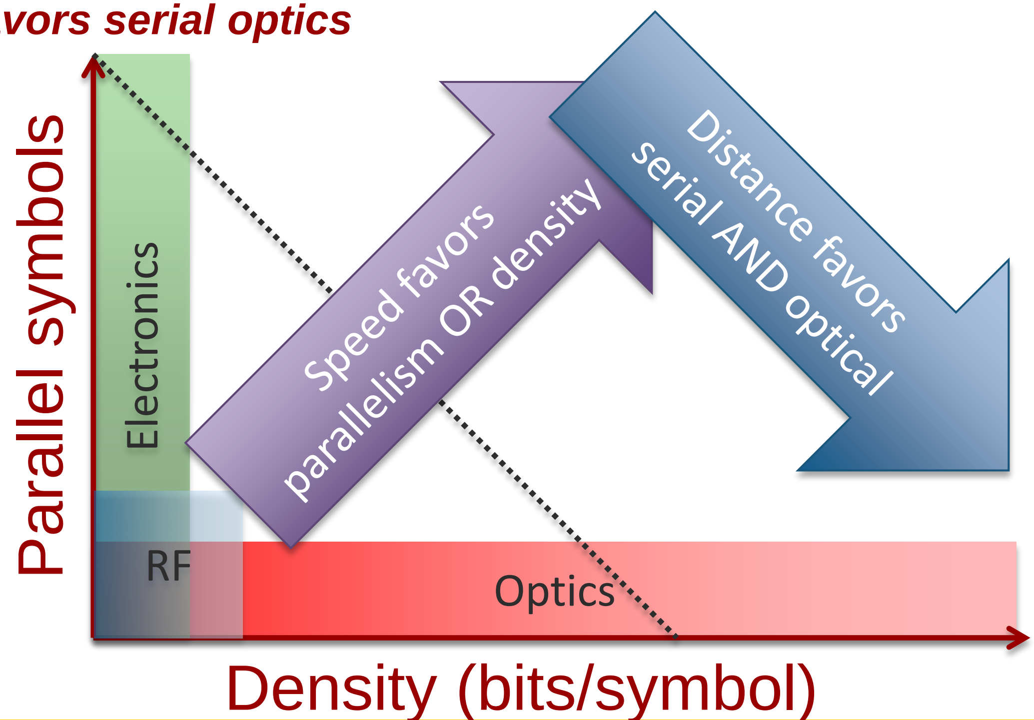
Multi-bit optical vs. electronic parallelism

- Speed favors serial optics or parallel electronics
  - High-speed electronics requires parallel low-density streams
  - High-speed optics requires serial high-density streams
- ***Distance favors serial optics***



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Computation *vs.* Communication

- High-speed transmission
  - Currently serial multibit optical encoding
  - Parallel channels are too costly to synchronize
- High-speed computation
  - Currently parallel electronic binary encoding
  - Serial exceeds electronics
- Implication
  - Compute and transmit in different formats
  - Conversion is required (“OEO”) and costly

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Other Benefits of Optics

- 60x faster
  - Optics: ~100 Gbaud * 4 bits/symbol (16 QAM) = 400 Gbps per link
  - Electronics: ~3.25 GHz * 2 bits/cycle (both edges) = 6.5 Gbps per link
- Supports similar integration
  - Concurrent streams using a single device (2 polarizations x 30 wavelengths)
  - 1/100 devices/chip but 60x streams per device
- Supports serial algorithms
  - Some functions can be simpler
  - 32-bit adder uses ~6 serial elements *vs*. >6,000 parallel

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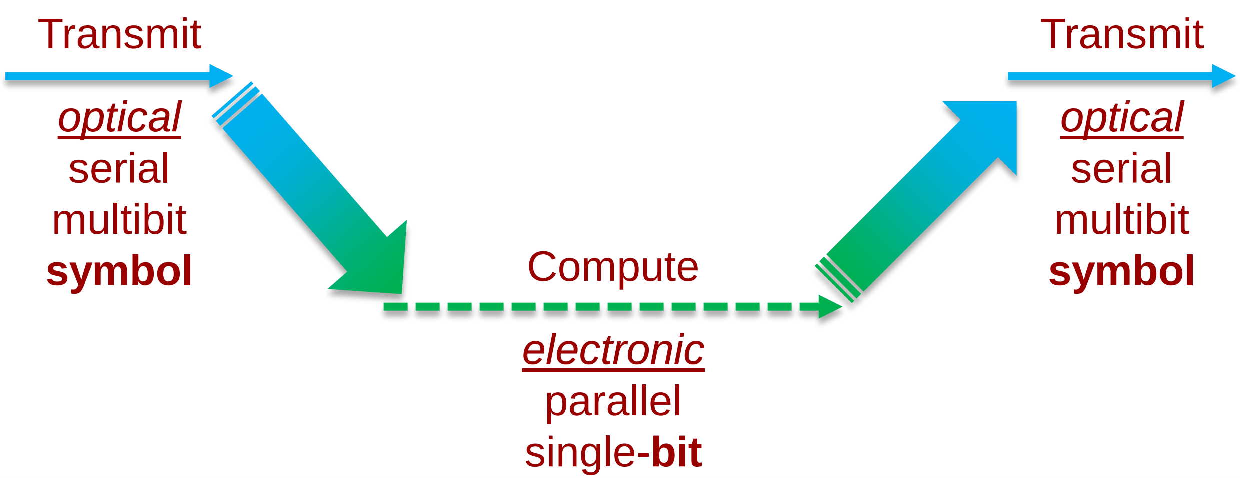
OEO *vs.* SBS

- Optical-electronic-optical (OEO)
  - Really <u>*symbol-bit-symbol*</u> (SBS) conversion
  - Convert from multibit symbols to on-off keying (OOK)
- Conversion is expensive
  - Power, complexity, performance



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Back to Basics

- Computation
  - Use state to manage symbol (sequence) translation
- Communication
  - Exchanging symbols to manage (endpoint) state
- These are related
  - Both use state
  - Both "translate" symbols
- Hypothesis:
  - What if both could share one encoding?

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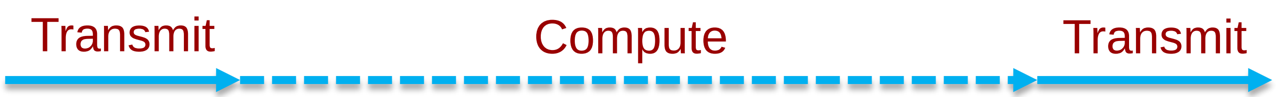
OTM Goals

- Avoid conversion
  - Compute in long-distance transmission format



optical
serial
multibit
symbol

- Explore a new domain of computation
  - Determine unique capabilities of native operations on transmission-format information

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Native Multibit-symbol Support

- Explore formats, value mappings
  - Phase, power, frequency, polarization dimensions
  - Direct increment *vs*. “hopscotch” strides
- Explore alternate logics
  - Transformational (*vs*. gated) functions
  - Serial/temporal asynchronous functions
- Potential for multidimensional encoding
  - *vs.* multivalued 1D encodings
  - *e.g.*, concentric QAM *vs*. spiral QAM

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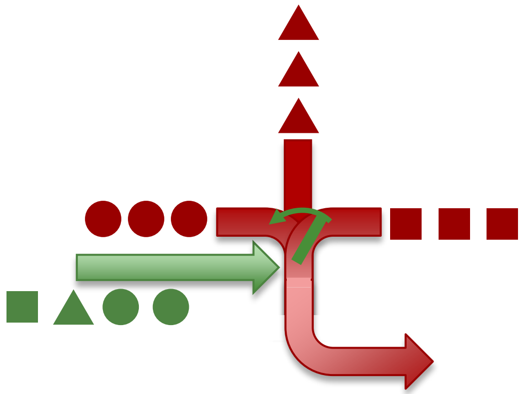
Functions

Gated functions

- Input selects other input(s) or constants (power rails)
- Requires constants, *i.e.*, symbol generation
- Requires clocking



Transformational functions

- Change input signal(s) into output signal(s)
- Self-synchronizing

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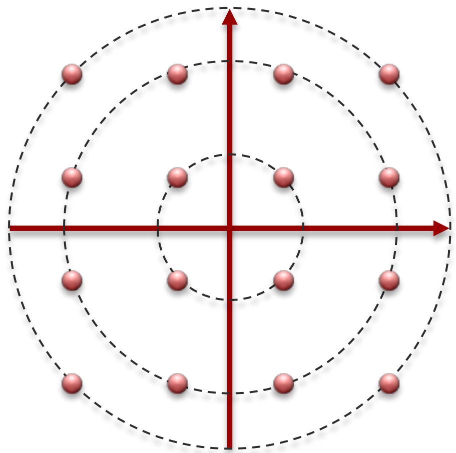
Coding

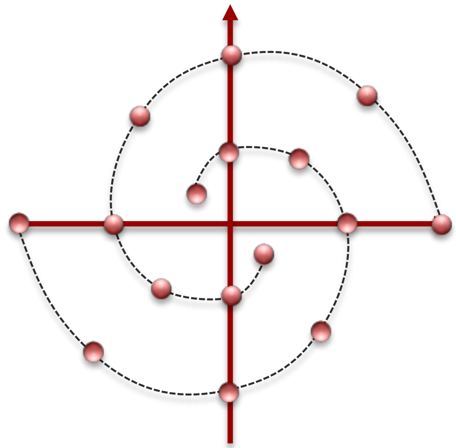
Current: Concentric QAM

- Uniform minimum distance between valid values

OTM: Spiral QAM

- Value-independent transforms





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New Models of Computation

- Extend logic for multibit optical symbols
  - What is required – a ring?
    - As in Boolean NAND or NOR,
      but with more than just binary values
    - *E.g.*, modulus integers under add/multiply
  - Non-ring functions vs. full λ-calculus
- Explore opportunities for Turing Machine variant
  - Minimal functions for completeness
  - Is computation possible with ephemeral I/O?
    (maximum look-forward/back within fixed ΔT)
  - Is computation possible with ephemeral state?

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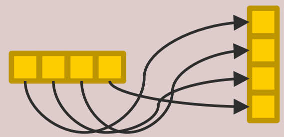
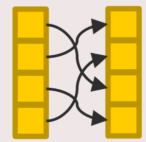
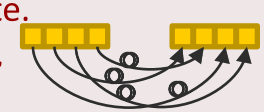
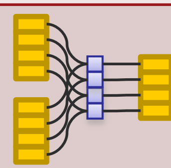
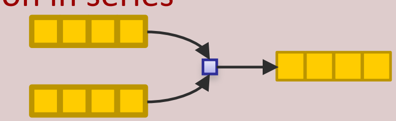
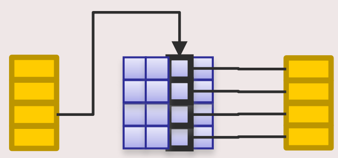
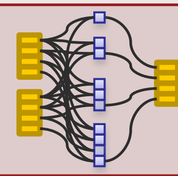
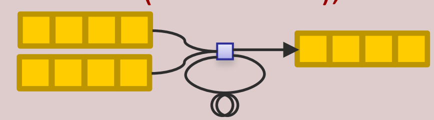
Exploring Functions:
Electronics vs. Optics

Input format	Convert to parallel 	✓ Serial data– native bit-stream 
Permute	✓ Fixed permutations are wires. Variable permutations require switching 	Time-shift to permute. 1 nonlinear element, 1 delay per symbol Needs tuning, switching, timing 
XOR / Booleans	N 2-input gates in parallel 	✓ 1 function in series 
Table Lookup	✓Index into a table . Table data stored in memory or as fixed wires 	Tapped-line correlator to select from N pattern generators **Optical Tapped Delay Line**
Add	Full-lookahead devices. N lookahead functions, each of O(N^2) elements 	✓ ✓ 1 function (6 elements), 1 delay 

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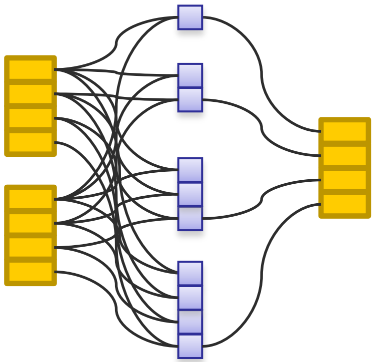
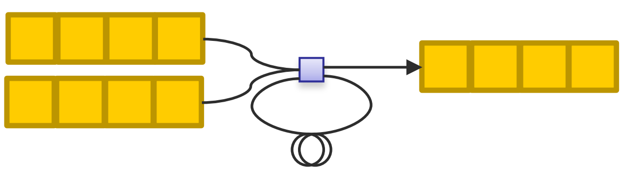
Adder Complexity

Electronics



Optics



- Parallel look-ahead (electronic) adder
  - Create, generate & propagate functions
    - $G_i = A_iB_i$
    - $P_i = A_i + B_i$
  - Compute carries
    - $C_{i+1} = G_i + P_iC_i$
    - $C_4 = G_3 + P_3G_2 + P_3P_2G_1 + P_3P_2P_1G_0$
    - J^{th} element = OR of J groups of 1..J parts i.e., each element is $O(J^2)$
  - Total complexity is $O(N^3)$ for N-bit width
- Serial (optical) adder
  - Notation:
    - AND (adjacent), OR +, XOR ^
    - A, B = inputs; S = output
    - C = carry
  - Generate sum, carry (optical adder)
    - $S_i = A_i \wedge B_i \wedge C_{i-1}$
    - $C_i = A_iB_i + (C_{i-1}(A_i \wedge B_i))$
  - Total complexity is 6 (indep. of width)

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Core Areas of Investigation

- Multivalue symbol transformations
  - Multibit logic/math
    (rings/groups – poss. beyond boolean)
  - Symbol transforms – not gating
- Serialization
  - Serial logic/functions
  - Time-based (vs. space-based parallelism)
- Ephemeral state
  - Limited "lookback"
    (like USC/ISI Tetris router conveyor queues)

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Potential Impact

- On-line processing
  - Data too large/high-capacity (or both) for off-line proc.
- Low-power
  - Processing without OEO/SBS conversion
- Examples:
  - Checksums / error coding and correction
  - Encryption and authentication
  - Packet filtering / virus scans
  - Transcoding
  - Data fusion (merging stream info.)
  - Data reduction (map/reduce)

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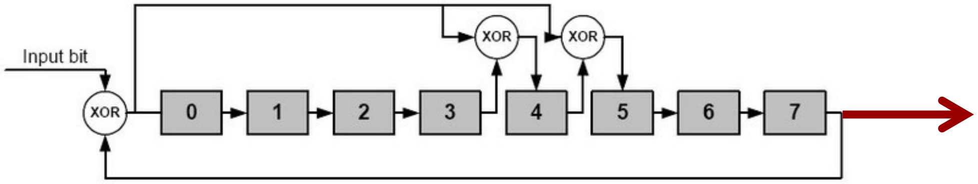
Use Case: Packet Filtering

- Digital optical processing to detect/remove packets
  - Link errors destroy packets
  - Corrupt packets consume capacity all the way to the receiver
  - On-line checks can detect and remove corrupt packets
- Example: Ethernet Cyclic Redundancy Check (CRC)
  - CRC8 uses XOR, shift
  - Correlator checks result against CRC in packet
- Other examples:
  - Other checksums
  - Error correction codes
  - Authentication
  - Encryption

polynomial : $x^8 + x^5 + x^4 + 1$



CRC- 8 generator

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Potential Risks

- Large space of alternatives
  - Symbol encodings
  - Mapping/meaning (symbol:value)
  - Logic/numeric functions
- Complex circuit constraints
  - Regenerative (level restoration)
  - Asynchronous
  - Transformational functions only – no gated values
- State persistence
  - Non-traditional model of computation
  - May constrain utility to on-line network processing

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Requirements

"Digital Transistor", Miller, *Nature Photonics* 2010

1. Cascadable
   - Stage N output drives stage N+1 input
2. Fan-Out
   - Output can drive at least 2 inputs
3. Logic-level restoration
   - Re-digitization
4. Input/output isolation
   - Immune to reflection
5. Absence of critical biasing
   - Robust to configuration variation
6. Logic level indep. of loss
   - Robust to signal weakness

OTM

1. Digital (3) -> nonlinear
   - Requires re-digitization
2. **Persistent -> multibit & serial**
   - Space-P. = transmittable
   - Time-P. = storable
3. **Asynchronous -> transformational**
   - Functions transform inputs, not gate them
4. **Turing-equivalent**
   -> new math, alphabet, semantics
   - Recursive (opterationl induction) (1)
   - Time-Persistent
   - Group (two operations, *etc.*)
   - Conditionals
5. Robust? (4,5,6)
   - Stable under variation (*vs.* ECL?)

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OTM Summary

- New approach to computation
  - Designed to native constraints of transmission
  - First-principles revision to new domain
- Symbol-based
  - Concurrent coding, function, and physical realization
- Collaborators:
  - Prof. Alan Willner, USC EE/Systems
  - Ph.D. students: Mortezza Ziyadi, Salman Khaleghi, Mohammed Reza Chitgarha

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