Architectural Components for a Practical Quantum Computer:

John Kubiatowicz
University of California at Berkeley

QARC: The Quantum Architecture Research Center

- Four Researchers:
  - Fred Chong (UC Davis)
  - Isaac Chuang (MIT)
  - Mark Oskin (U Washington)
  - John Kubiatowicz (UC Berkeley)
- Funny quote on someone's web site:
  - "Perhaps appropriately, given the uncertainty principle that underpins quantum mechanics, this 'center' does not have a specific physical location, but is rather a community of several research labs led by Fred Chong, Isaac Chuang, and John Kubiatowicz."

What does an architect (i.e. me) Think about?

- Big systems:
  - Millions or Billions of interacting elements
  - Not 7-10 bits
- Buildable systems:
  - Constructed from smaller, easily composed elements
  - Possible to verify functionality
    - Over 50% of modern design teams for verification
    - Verifying a quantum bit -- harder than asynchronous logic???
  - Easy to fabricate
- Programmable systems:
  - Can be directed to do some desired task
    - Easy use of abstraction, high-level languages, compilers
    - Could use automated programming techniques, but still need some human-specified goal set
  - Can be debugged

Does this have any relevance to Quantum Computing?

- Big/Scalable?
  - Has to be something with easily repeatable units
  - Given current sophistication of fab technology:
    - This probably means silicon-based…?
- Buildable?
  - Components that we understand means:

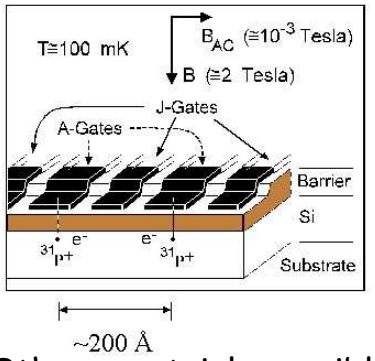
    That are bigger than a bit!
  - It also means that we can multiplex/reuse pieces
  - Possibly with CAD tools?
- Programmable?
  - Yeah, well

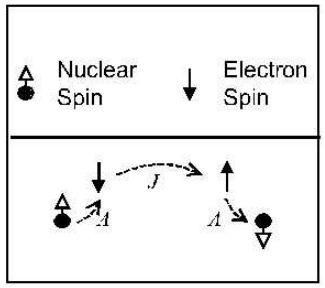
Classical Computer Components

- Von Neumann architecture has:
  - Memory, CPU, Registers, I/O
  - Very powerful abstraction/good building blocks
- Physical Extent of components (say on 2-d chip):
  - Means that we need WIRES
- Ground/VDD?
  - Nice source of 0 and 1
- Signal preservation through coding
  - In principle could put ECC everywhere
- Extensive design flow:
  - CAD tools for producing circuits/laying them out/fabricating them, etc.

Start with Scalable Technology:

- Big interest in Kane proposal, for instance

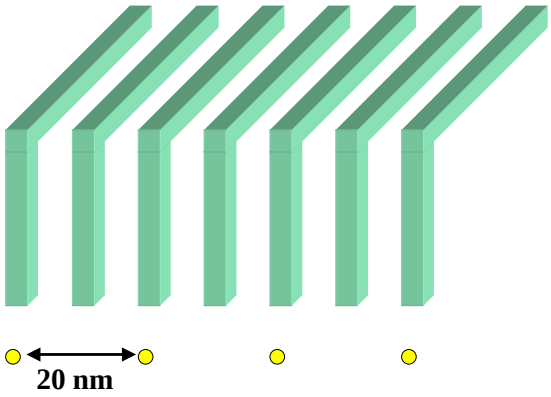




- Others certainly possible (No offense intended!)

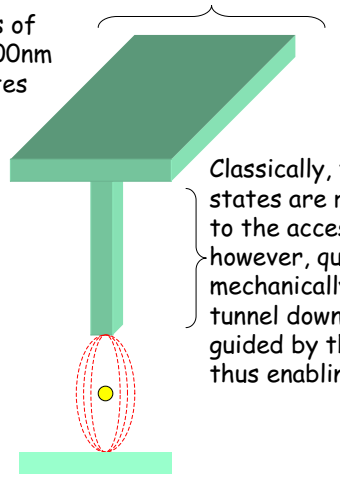
Interesting problem: Classical Interface to Quantum Domain?

5nm access points contain only a handful of quantum states at temp < 1K



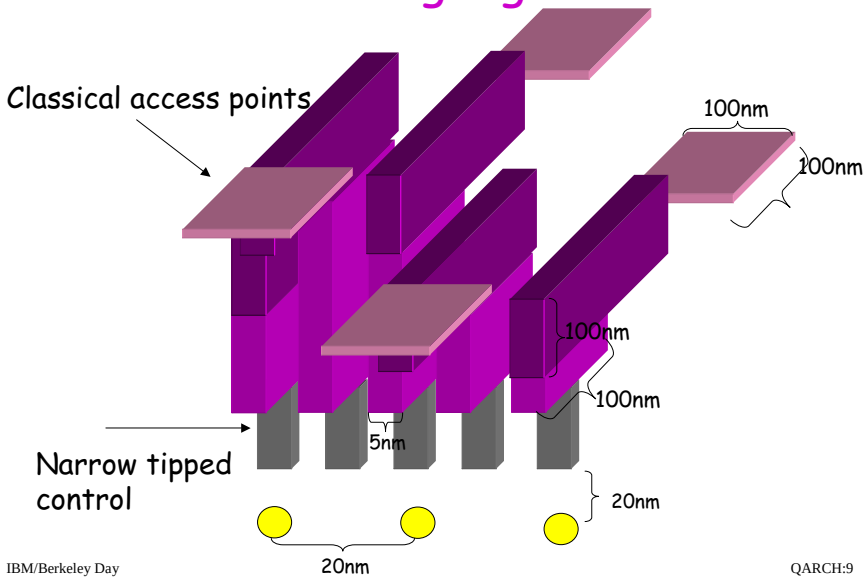
Perhaps a solution?

As two physical dimensions of the access point exceed 100nm thousands of electron states are held.

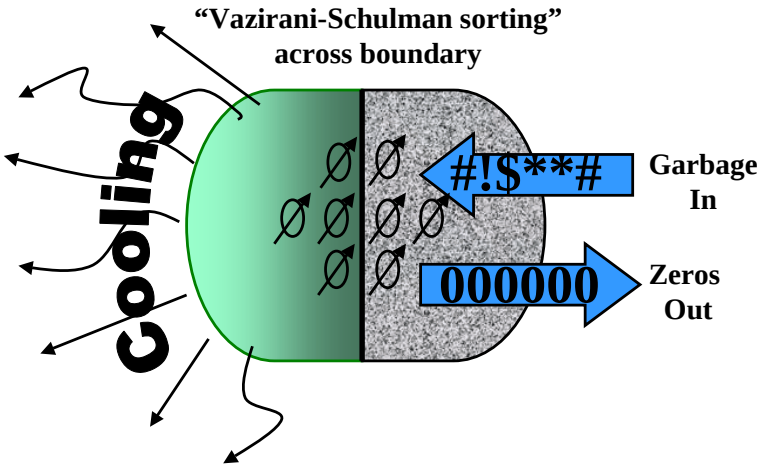


Classically, these states are restricted to the access point, however, quantum mechanically they tunnel downward, guided by the via, thus enabling control.

Pitch-matching nightmare??



Example of Components: The Entropy Exchange Unit



Why is this important?

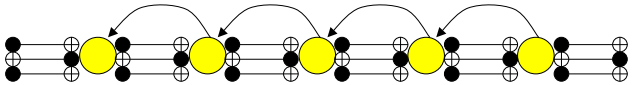
- Initialized states (zeros, for instance) required for:
  - Initialization of Computation (not surprising)
  - Error correction (continuous consumption)
  - Long-distance quantum transport (wires)
- Entropy exchange probably needed *everywhere!*

What is involved here?

- Substrate capable of quantum computation
- Possibilities for cooling:
  - Spin-polarized photons ⇒spin-polarized electrons ⇒spin-polarized nucleons
  - Simple thermal cooling of some sort
- Two material domains:
  - One material in contact with environment
  - One material isolated
- Quantum computing across boundary
  - Ack! Most basic operation requires some computing

What about wires?
A *short* quantum wire

- Key difference from classical:
  - quantum information must be protected/restored!!
  - Cannot copy information (no fanout)
  - Cannot (really) amplify this info
- Short wire constructed from swap gates
  - Each step requires 3 quantum-NOT ops (swap)



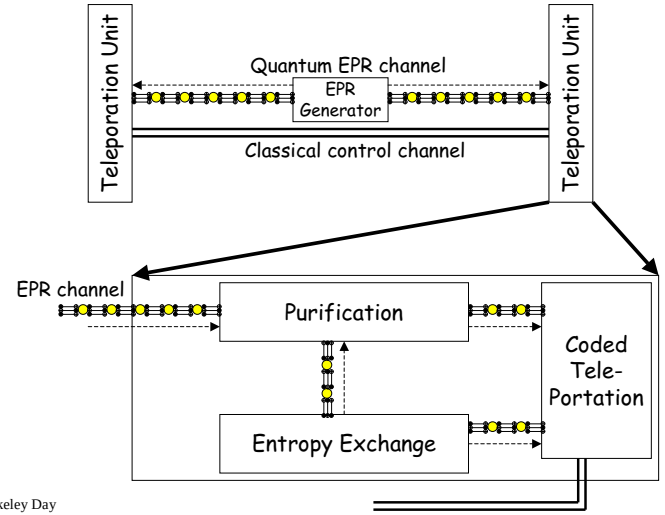
Why short wires are *short*

- Limited by decoherence
- Threshold theorem => distance
  - For some assumptions ≈ 1.8mm (very rough)
  - Very coarse bounds so far
- Can make longer with "repeater"?
  - Essentially this is multiple short wires Separated by error correction blocks

How to get longer wires??

- Use "Quantum Teleportation"
  - Transfers EPR pairs to either end of "wire"
  - Measures state at source, transfers bits to dest
  - Source bit destroyed at source, reconstructed at dest
- Key insight:
  - EPR pairs are *known* states
- No need to protect them
  - Purify the good ones
  - Discard the bad

Architecture of a long wire



Long wires

- COMPLEX!!! Much computation at either end
  - Need to purify EPR pairs
  - Need to measure
- Can be of "arbitrary" length
  - A 10mm wire sustains nearly peak bandwidth
- Latency matches classical latency
  - Pre-communicate EPR pairs/pipeline purification
  - Latency is constant: teleportation operation
- Code-conversation for "free"
  - Facilitates Processor <-> Memory communication [COC+02]

Conclusion

- Perhaps not too early for *Architects* to start thinking about quantum computing
- Important non-classical components:
  - Entropy exchange units/EPR generators
  - Wires: Multiple varieties
- Other things (I didn't even bother to talk about):
  - Memory/CPUs, etc
  - CAD tools
  - Etc.
- Will we ever *really* have to worry about 1000s or millions of bits?
  - Hopefully