Architectural Components for a Practical Quantum Computer:

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Why Quantum Computers?

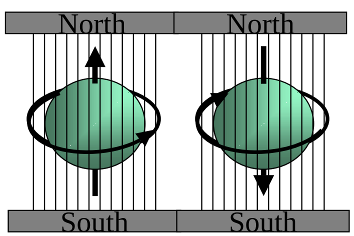
- Interesting potential?
  - Shor's algorithm: factors in polynomial time!
  - Grover's algorithm: Finds items in unsorted database in time proportional to square-root of n
  - Break homomorphic encryption algorithms
- They are cool to think about!
  - (< 1 Kelvin in some cases!)
- Interesting architectural challenges!
  - If we ever get to large quantum computers…

Today: BABY STEPS

Use of "Spin" for QuBits

Spin ½ particle: (Proton/Electron)

Representation: |0> or |1>

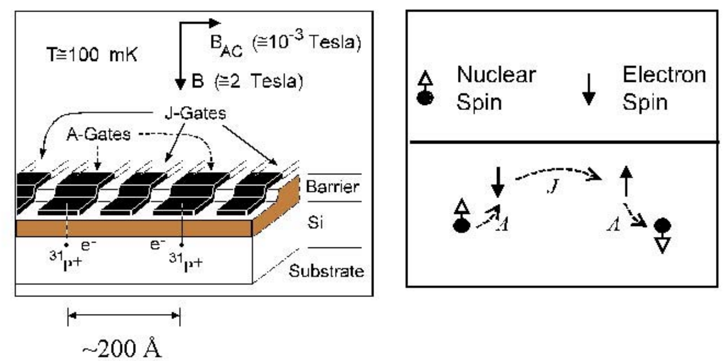


- Quantum effect gives "1" and "0":
  - Either spin is "UP" or "DOWN" nothing in between
- Superposition: Mix of "1" and "0":
  - Written as: $\Psi = C_0|0\rangle + C_1|1\rangle$
  - An n-bit register can have 2^n values simultaneously!

$$\Psi = C_{000}|000\rangle + C_{001}|001\rangle + C_{010}|010\rangle + C_{011}|011\rangle + C_{100}|100\rangle + C_{101}|101\rangle + C_{110}|110\rangle + C_{111}|111\rangle$$

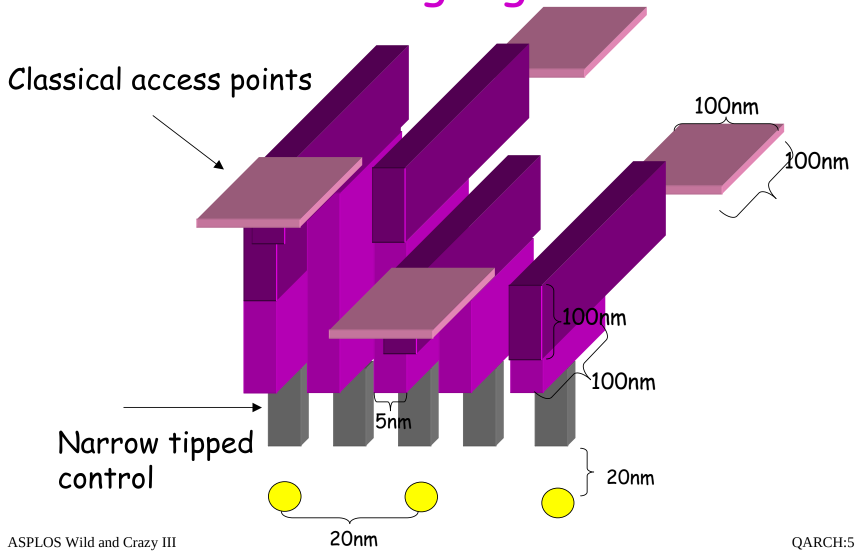
Start with Scalable Technology:

- For instance Kane proposal



- Others certainly possible (No offense intended!)

Interesting fact #1: Pitch-matching nightmare??



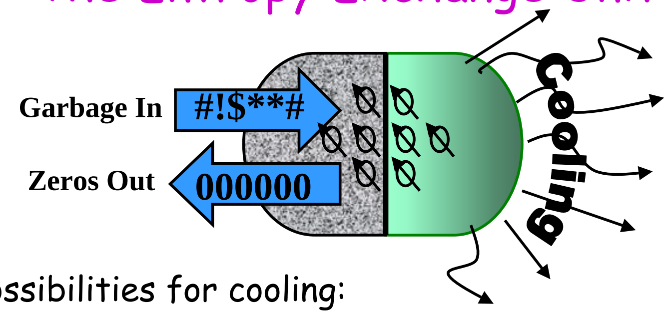
Classical Computer Components

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

Why are initialized states important?

- Initialized states (zeros, for instance) required for:
  - Initialization of Computation (not surprising)
  - Error correction (continuous consumption)
  - Long-distance quantum transport (wires)
- Paradox:
  - Insulate from environment for quantum computing
  - Tie to environment for initialization

Interesting Ubiquitous Component: The Entropy Exchange Unit



- 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

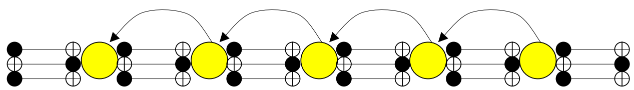
Interesting Fact #2: Wires are non-trivial

- No-cloning theorem:
  - Cannot copy quantum states
  - $\Psi = C_0|0\rangle + C_1|1\rangle$
  - *Can* transport it…

- News Flash: Classical Wires copy state!!!
  - Also: Repeaters/amplifiers: probably right out!
- Fanout is right out!
  - At least in direct sense

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)

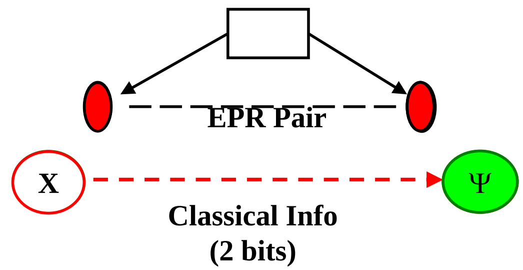


Why short wires are *short*

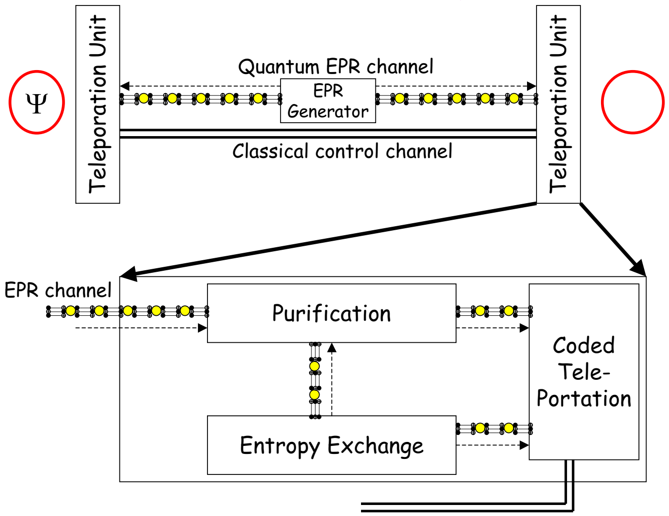
- Limited by decoherence
- Threshold theorem => distance
  - For some assumptions ≈ 1 μ (very rough)
  - Very coarse bounds so far
- Can make longer with "repeater"?
  - Essentially this is multiple short wires Separated by error correction blocks

Getting Longer Wires

- Use "Quantum Teleportation"
  - Transfers EPR pairs to either end of "wire"
  - Measures state at source, transfers bits to dest
  - Source bit destroyed, reconstructed at dest



A Long Quantum Wire: Use Quantum Teleportation



Conclusion

- Perhaps not too early for *Architects* to start thinking about quantum computing
- Important non-classical components:
  - Wires: Multiple varieties
  - Entropy exchange units/EPR generators
  - CAD Tools?
- Quantum Architecture Research Center: http://feynman.media.mit.edu/quanta/qarc/index.html
  - Studying Memory, CPUs, Wires, etc
  - Physics of components and classical/quantum interface
  - Exploring CAD tools:
    - Fabrication
    - "switch-level simulation": evaluate algorithms
    - Quantum VHDL
  - New ways of describing Quantum Computing
- Funding from DARPA, NSF