Quantum Architectures

June 1, 2005

Computing?

e of computing devices that exhibit quant
chanical behavior

ehavior of isolated ions

Bose-Einstein condensate in a magnetic well

hoton interactions

ire and transistor interactions in the near future

e computing model is largely unexplored

$\subseteq ?$ QP $\subseteq ?$ NP

e usage model is still being debated

hy are Architects Involved

- e know what the “killer app” will be
  - Error correction will be >99% of the work
- e physicists don’t know computation
  - “Don’t worry, it’s polynomial…”
- e theorists don’t know physics
  - “Simplify the problem by removing communication…”

- short, architects can be the reality check
  - Identify physical bounds that supersede theoretical on
  - Determine what aspects of computation will be the m challenging

Outline

- hat makes quantum different?
  - Quantum bits
  - Operations and measurement
  - Decoherence
- hat will a quantum computer look like
- uantum architecture research at UW
  - Current research: Simulation
  - Building quantum wires

Classical vs. Quantum

sic element: 0 or 1

ts are independent

ata may be copied destroyed at will

ata is static

- Bits are continuous va
- Bits may be entangled interfere
- Data may not be copie
- Operations must be reversible
- Data decoheres with t

Qubits: Quantum Bits

and qubits both have two states: 0 ar

perposition:

ubit may be in both states simultaneously

ase:

ubit may have a negative quantity of a st

uantum States and Measuremen

e qubit probabilistically represents two states

$$a\,|0> + b\,|1>$$

ch additional quibit doubles the number of sta

$$a\,|00> + b\,|01> + c\,|10> + d\,|11>$$

easurement sends a qubit into a classical stat

is may alter the states of other qubits

$$a\,|00> + b\,|11> \text{ (EPR state)}$$

easurement and Copy Protectio

- uantum data cannot be copied
  - Copying involves a read and a write
  - “Reading” destroys the state
- uantum data can be transferred
  - One qubit can swap its state with another
  - Quantum state can be “teleported” over infinite distance (but the sender loses the data)
- any quantum algorithms are probabilistic d involve iteration

Other Operations

easurement: the only irreversible operati

l other operations are reversible

2nd Law: Reversible operations conserve ener

“Not” is reversible

“And” and “Or” are not reversible

ost “traditional” operations must produce

ditional output

How do you make “+” reversible?

Scratch bits must be protected

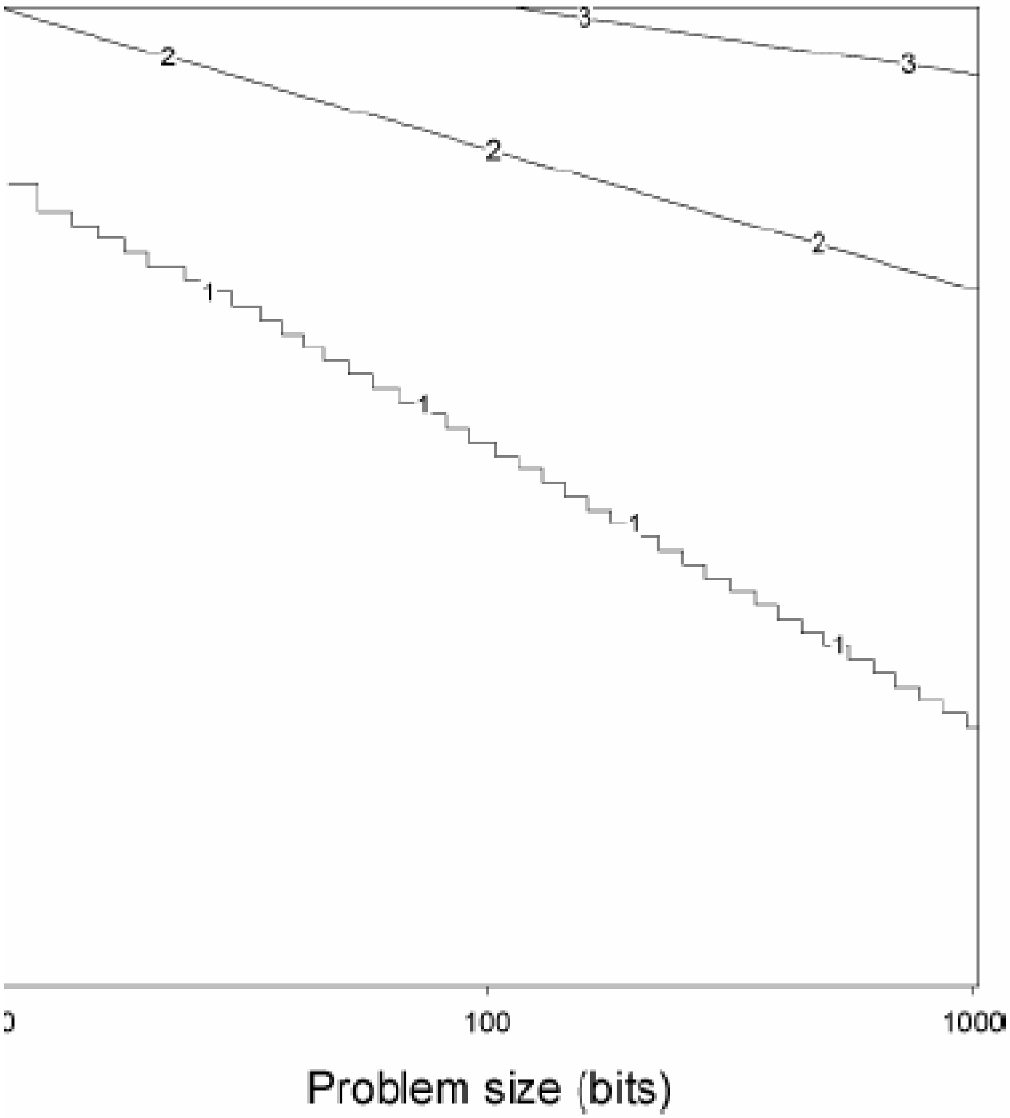
Noise: Decoherence

- eoretical systems are “closed”
  - No energy may enter the system unless explicitly introduced
- al systems can’t be completely isolated
  - Performing an op adds “noise” to a qubit
  - Over time, qubits will simply “decohere”
  - At higher temperatures (higher energy), decoherence occurs more quickly
- e will need massive cooling systems
- y usable quantum system will require error

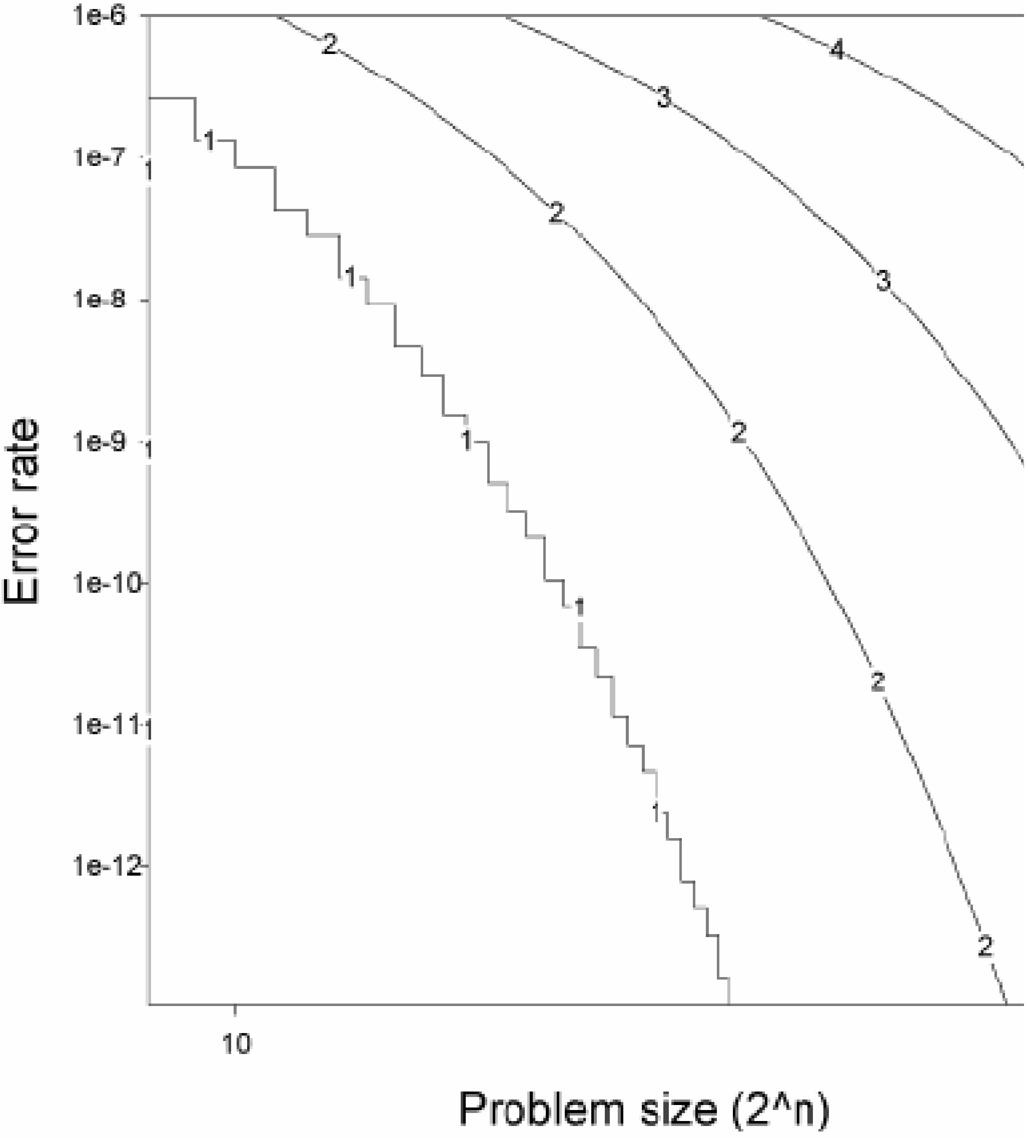
rror Correction is Crucial

- ror correcting codes are available
  - Operations exist for computing on encoded dat
  - Since qubits cannot be read, an error correctio routine manipulates the coded bits to fix errors
- ror correction must often be applied cursively to error correction routines
- e Threshold Theorem
  - An error rate of 10^{-4} per op can be tolerated
  - This error rate requires nearly continuous error correction

Recursion Requirements



Shor's



Grover's

To Summarize…

uantum bits are awesome

…except that no one has really done anything amazing with them (yet)

…because measurement really hurts

oring and moving data will be difficult

Decoherence limits storage and transit time

e know what quantum computers will do

Error correcting…all the time

rforming computation in the presence of

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Pick a Technology

- hat device technology will be used?
  - Who knows…
- evelop first order assumptions
  - Classical control of quantum gates
  - Silicon to interface and control
    - Provides rough size constraints
  - Individual control of quantum bits
- ck a likely technology that fits
  - For example, ion traps

Consider Building Blocks

Processor: Computation

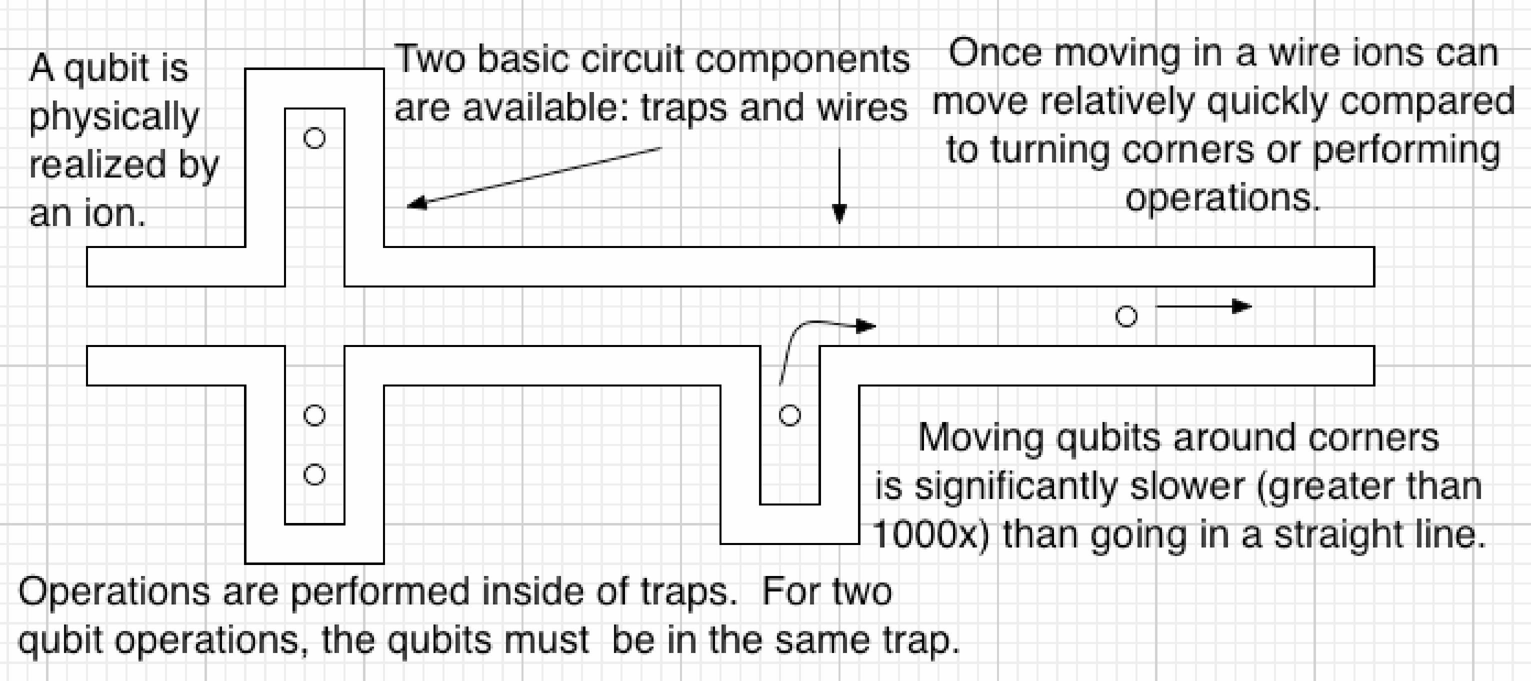
- Several sets of universal gates exist
- Different device technologies can more easily implem some gates than others
- Measurement and “zero” creation is also important

emory: Storage

- Storage is difficult because of decoherence
- Constant error correction may be performed
  - Decoherence-free subspaces are being researched
- Hence, memory looks a lot like the processor

Interconnect: Communication

reger-Stickles and Balensiefer



A qubit is physically realized by an ion.

Two basic circuit components are available: traps and wires

Once moving in a wire ions can move relatively quickly compared to turning corners or performing operations.

Moving qubits around corners is significantly slower (greater than 1000x) than going in a straight line.

Operations are performed inside of traps. For two qubit operations, the qubits must be in the same trap.

e computer is a grid of traps and wires

ch trap has a flexible gate that can perform easurement or a quantum op

mmunication is performed by moving ions

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  - Representing quantum algorithms

mulating Quantum Compute

nt work by Kreger-Stickles, Balensiefer, and C

compare architectures, performance data is n

ulation is the only choice

Fully" simulating a quantum system takes exponential

y modeling only reliability, can be done in linear time

e Simulation Infrastructu

n error correction compiler

Takes a quantum algorithm for one specific inpu

Produces a fault tolerant version of the algorith

device scheduler

Takes a program and an architecture

Produces a static operation and communication schedule

reliability simulator

Takes a scheduled application and architecture

Produces performance and reliability metrics

Preliminary Results

ror correction is less effective than we assum

Correcting errors requires that bits be moved

e Threshold Theorem is optimistic

Realistic execution constraints (communication) limit acceptable error rate

The realistic threshold is four orders of magnitude wo

antum computer size will be limited by the er

te of the underlying technology

The further bits have to move, the lower the rate has be

ilding a Quantum Wire (Oski

get technology is Kane’s silicon ion-tr

ons are embedded into silicon traps

- Spin of 31P holds quantum state
- Ions spaced ≤ 20nm apart for quantum effect to o
- ≤ 1.5Kelvin for reasonable coherence time

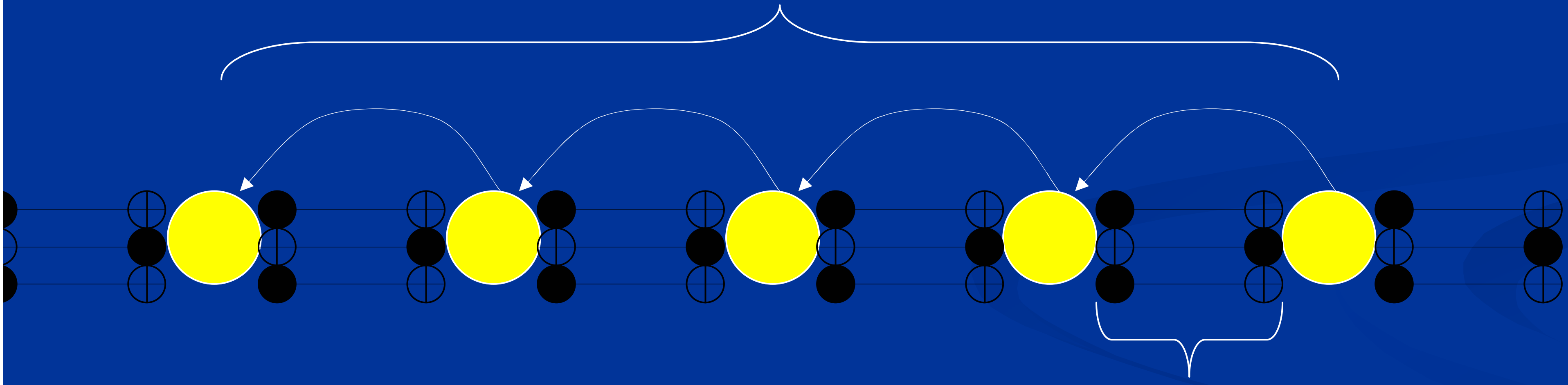
ocal magnetic field arbitrates gates

- Controlled by “classical” pins
- Driven by high frequency (10-100Mhz) clock
- Gated by “lower” frequency (0.01 – 10Mhz) clock

A Short Quantum Wire

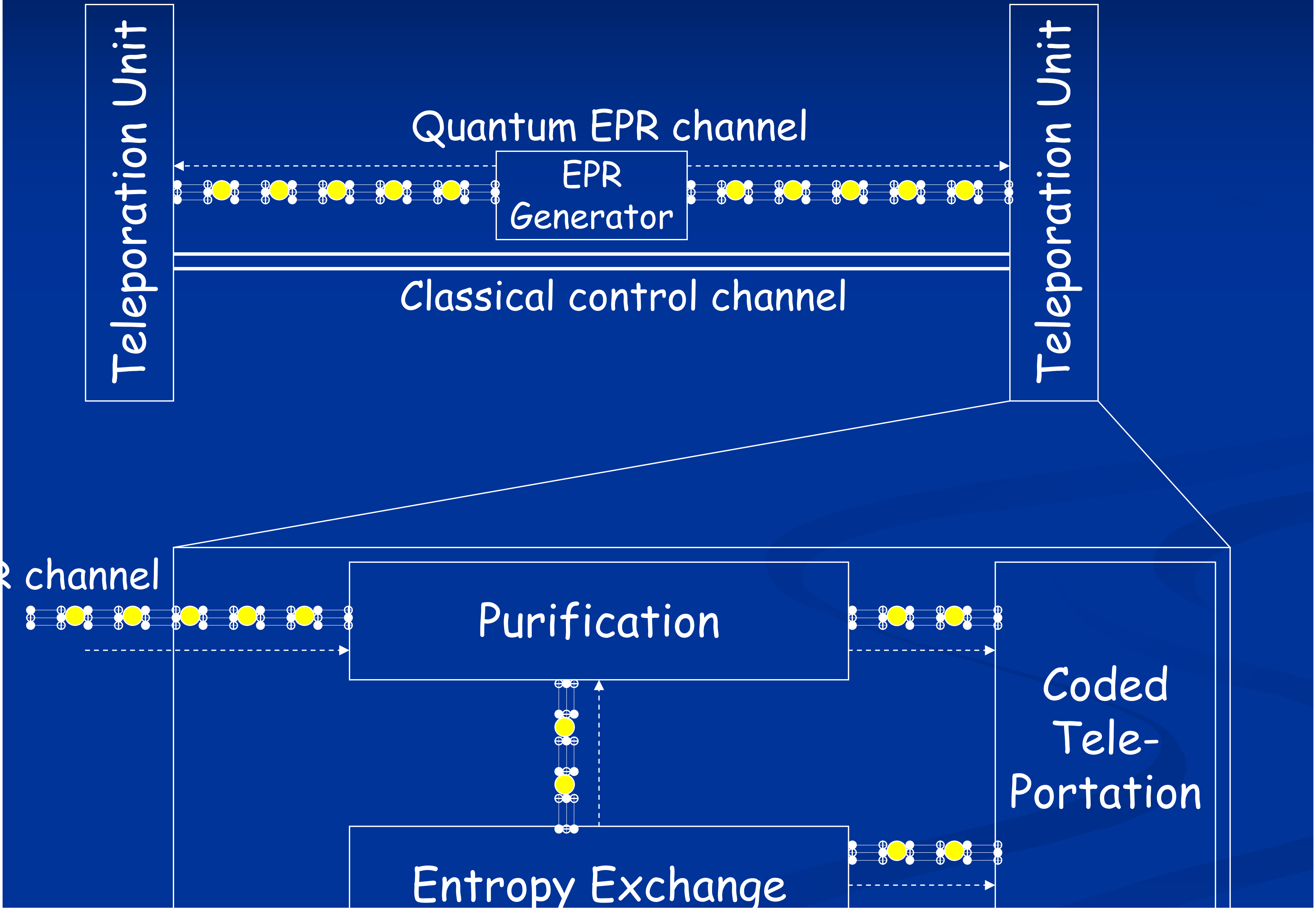
nstructed from swap gates

Unless the particle that holds the quantum state physically moves, the information “flows” in discrete steps from particle to particle.



Each step requires 3 quantum controlled-not operations, effectively performing a “swap” of the quantum states.

rchitecture of a Long Wire



Teleporation Unit

Quantum EPR channel

EPR Generator

Classical control channel

Teleporation Unit

channel

Purification

Coded Tele-Portation

Entropy Exchange

Two Possible Wires

ort range: swapping-channel

- “Pitch matching” causes structural concerns
  - Qubits are 20nm apart, so control is limited to 5nm
  - @ 1.5 Kelvin, cannot drive an AC current
  - Other dimensions must be increased to > 100nm
- Length is limited due to decoherence

ng range: teleportation-channel

- Length is arbitrary
- Many additional structures are required
- Bandwidth is constrained by EPR pair productio

presenting Quantum Computati

lop an alternative notation for quantum computing

presentation: dealing with groups of bits is ha
- nsure operations are insensitive to state space size
- troduce shorthand for common entangled states
- acilitate computation on large, highly entangled states

asoning: interesting states are difficult to iden
- entify quantum properties explicitly
- efine operations by the quantum properties they induc
- avor local transformations over global ones

An Example: EPR Pairs

atrix notation:

$$\begin{matrix}1\\0\end{matrix}\Big]$$

$$\begin{matrix}1\\-1\end{matrix}\Big]\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix},\ \begin{bmatrix}1\\0\end{bmatrix}$$

$$\otimes\begin{bmatrix}1\\0\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$$

$$\begin{matrix}0&0\\0&0\\0&1\end{matrix}\Bigg]\left(\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\1\end{bmatrix}\right)=\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\0\end{bmatrix}$$

In the algebra:

$$H(x)\rightarrow x^0 : x^0 + x^1 \parallel x^1 : x^0$$

$$CNot(x,y)\rightarrow x^0 : x^0 y \parallel x^1 : .$$

$$qubit\ p \ \Rightarrow p^0$$

$$qubit\ q \ \Rightarrow q^0$$

$$H(p)\ on\ p^0 \Rightarrow p^0 + p^1$$

$$CNot(p,q)\ on\ (p^0 + p^1)q^0$$

The High Order Bits

uantum architecture is a wide-open field

  We can’t even agree how to build wires!

chitects have an important role

  We act as intermediaries between the physicist and algorithm designers

you know how to do error correction well, u could become famous