Nanoscience and Quantum Information Science in the Army

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Outline

- **Nanoscience**
  - Electronic and Photonic Band Engineering
  - Chemical and Biological Agent Detection
  - Nanoscience for the Soldier
- **Quantum Information Science**
  - Quantum Communication
  - Quantum Computing

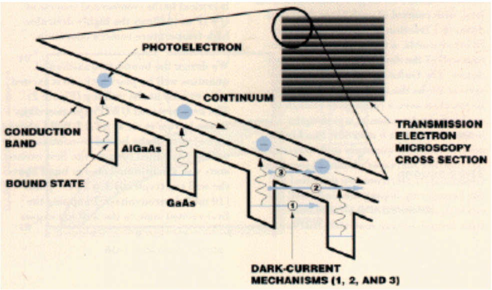
Electronic and Photonic Band Engineering

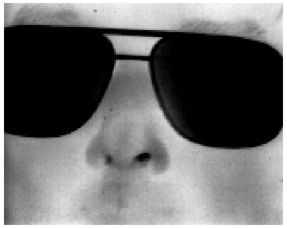
Nanoscience in the Army

IR Sensors and Sources

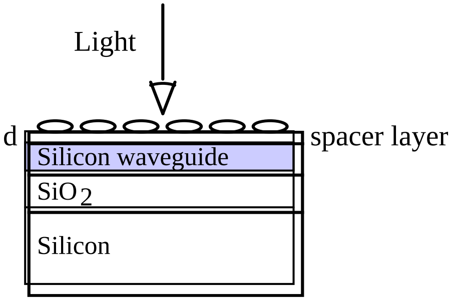
- **Advanced Photodetectors**
  - **Quantum Well Infrared Photodetectors**
    - Use electronic band engineering and nanofabrication techniques
    - Multispectral IR imaging
  - **Uncooled Infrared Detectors**
    - Uses nanofabrication and advanced materials
  - **Nanoparticle-Enhanced Detection**
    - Increase light detection by 20X
- **Quantum Cascade Lasers**
  - **IR Lasers for Target Designation and Countermeasures**
    - Objective: Compact, pulsed, high power 300K IR lasers
  - **IR Lasers for Agent Detection**
    - Objective: Tunable or multi-wavelength, single mode IR lasers

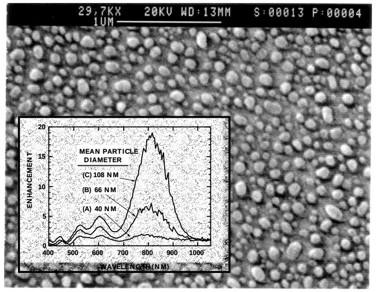
Quantum Well Infrared Photodetectors



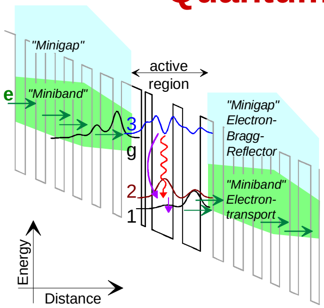


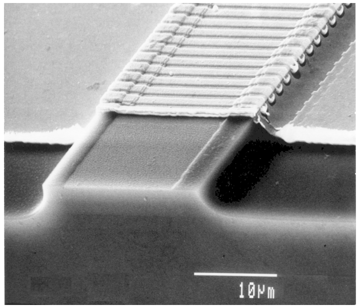
Nanoparticle Enhanced Detection





Quantum Cascade Lasers



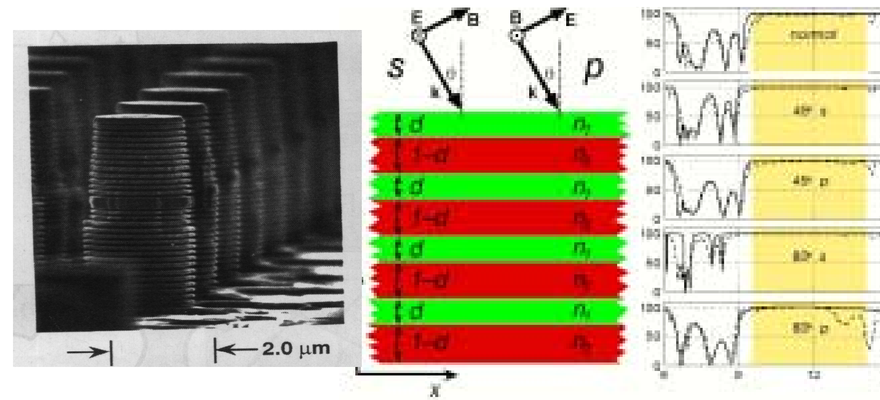


Photonic Crystals

- **Photonic Crystals**
  - **"Designer Mirrors"**
    - Periodic arrangement of dielctrics and/or metals
    - Reflect radiation
      - — Over band of frequencies
      - — Transparent otherwise
- **Types**
  - **1 D Photonic Crystals**
    - "Quarter wave stacks"
    - New omnidirectional reflectors
      - — Omniguide
  - **2 D Photonic Crystals**
    - Used in nanolasers, optical fiber
  - **3 D Photonic Crystals**
    - Reflect radiation
      - — From all directions
      - — From all polarizations

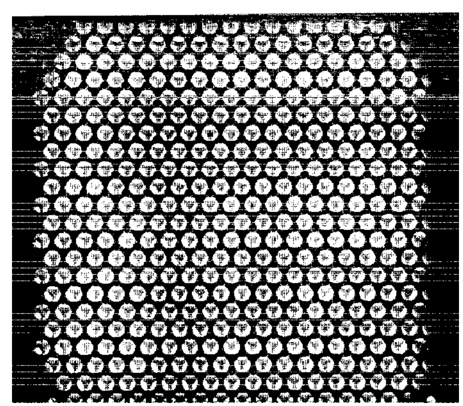
1D Photonic Crystals

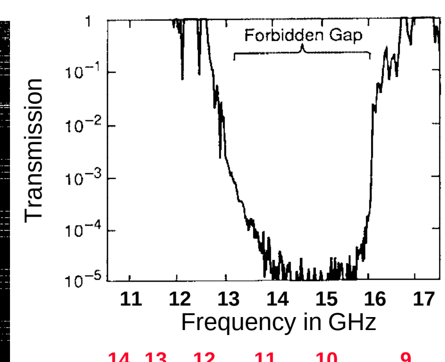
John Joannopoulos, MIT



3D Photonic Crystal

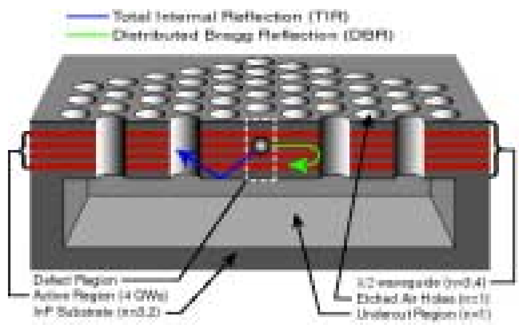
Eli Yablonovitch, UCLA

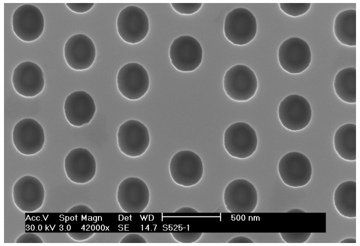


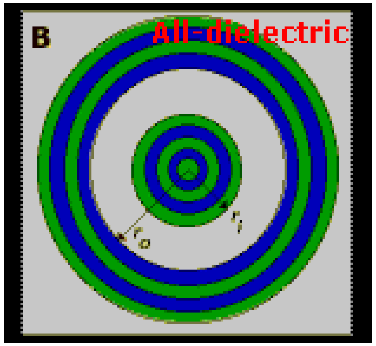


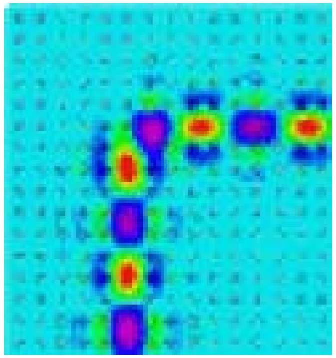
Photonics

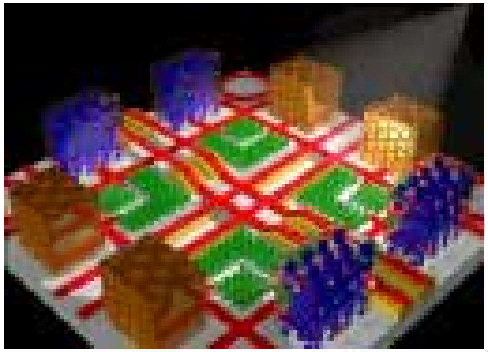
- **Lasers**
  - **Smallest possible laser cavity**
    - Thin, 2D photonic crystal
    - Low Threshold
- **Light Emitting Diodes**
  - **Improved emission efficiency**
  - **Improved collimation**
- **Waveguide**
  - **Omniguide fiber and coax**
  - **Photonic crystal fiber**
- **Integrated Photonics**
  - **Optical routing, filtering, and processing on a chip**
- **Laser Eye/Sensor Protection**
  - **Enhanced nonlinearities for optical limiting**











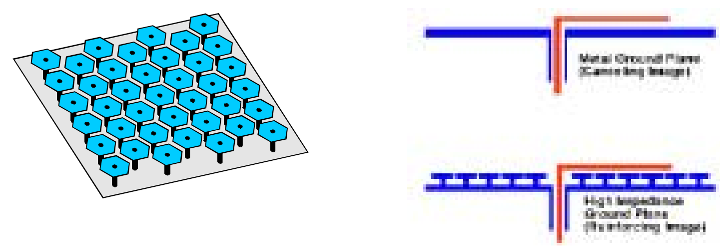
Antennas

Army Research Office

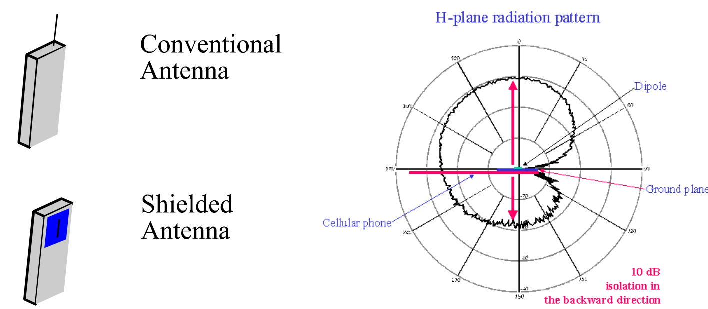
- **Soldier Antenna Issues**
  - **Proliferation**
  - **Vulnerability**
  - **Power consumption**

- **High Impedance Ground Plane**
  - **Metallic Photonic Crystal**
    - Antenna ground plane
      - — Conformal
      - — Efficient
    - Commercial application
      - — Cordless telephones
      - — Wireless LANs and PANs
    - Military application
      - — GPS
      - — Advanced Radar

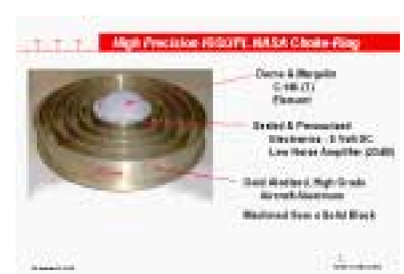
High Impedance Ground Plane



Improved Cordless Telephone Antenna



Sub-meter resolution, Jam-resistant GPS



Tactical Ops

Chemical and Biological Agent Detection

Nanoscience in the Army

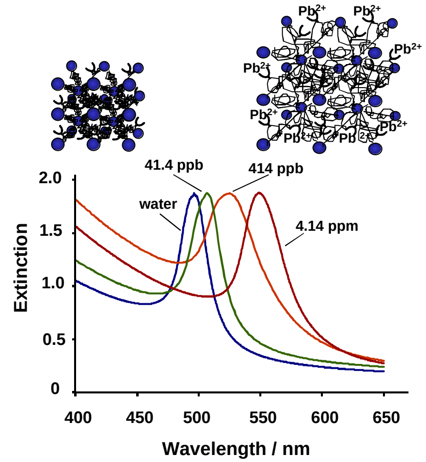
Chemical Agent Detection

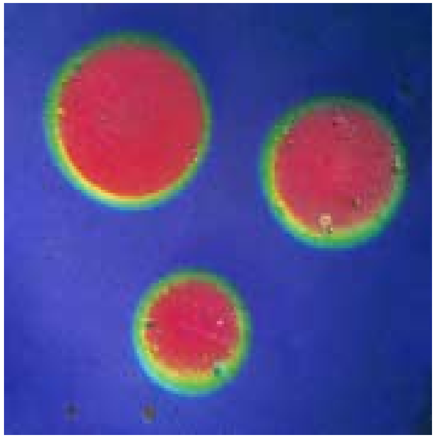
Sanford Asher, Univ. of Pittsburgh

Army Research Office

- **Point Detection**
  - **Need**
    - Detect water-borne agent
  - **Problem**
    - Sensitivity & durability
- **Solution**
  - **Photonic crystal-based colorimetric detection**
    - Self-assembled colloidal crystalline array
    - Attach receptors to colloids
      - Chelation recognition group
      - Enzymes
    - Agent causes photonic crystal to change size/color
  - **Results**
    - Lead detector to 40 ppb
    - In-vivo glucose monitor

Lead Detection





Glucose Detection

Fig. 1 Concept for glucose sensi
for tear fluid and for implants. Th
diffracted defines the glucose con

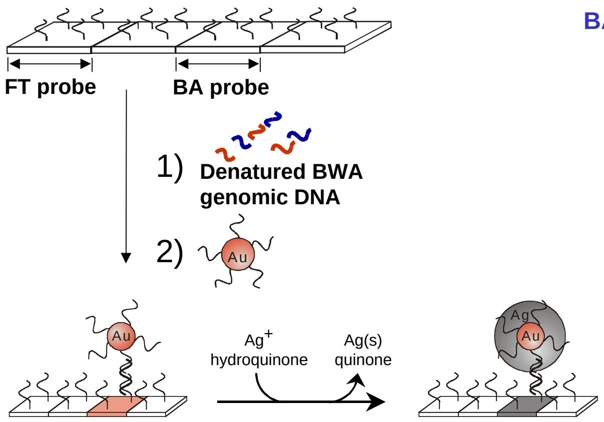
Biological Agent Detection

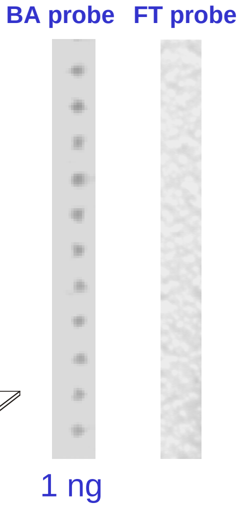
Chad Mirkin, Northwestern Univ.

- **Point Detection**
  - **Need**
    - Simple, fast, selective
  - **Problem**
    - Amplification requires PCR
- **Solution**
  - **Nanoparticle-based colorimetric detection**
    - Attach DNA to Au nanoparticles
      - Agent provides linking DNA
      - Ag amplification of signal
  - **Results**
    - Anthrax Detected
      - 30 nucleotide region of a 141-mer PCR product (*blue dot*)
    - Sensitive and selective
      - <10 femtomole detected
      - Detect single mismatch
    - Simpler and cheaper
      - DNA detection without PCR

Biological Integrated Detection System

Colorimetric Detection of Anthrax





BA = Bacillus Anthracis
FT = Francisella Tularensis

Nanoscience for the Soldier

Nanoscience in the Army

Materials and Textiles

- **High Strength, Ultra-lightweight Materials**
  - Ballistic protection
  - Lighten carriage, shelters, packaging, small arms
  - *Nano ≠ lightweight*

- **Adaptive, Multi-function Materials**
  - Chameleon skin
  - Interactive clothing
  - Eye/sensor protection
  - Energy harvesting
  - Water recovery
  - Flexible, robust packaging

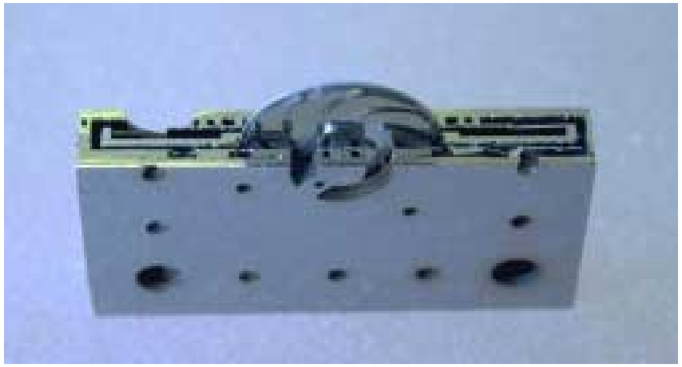
Reduce the Soldier's Load

Power and Cooling

- **Primary Power Sources**
  - Fuel Cells
  - Batteries
  - Micro-Turbines
- **Supplemental Power Sources**
  - Photovoltaics & Thermo-PVs
  - Thermoelectrics
  - Piezoelectrics for Energy Harvesting
- **Cooling**
  - Vapor Compression
  - Thermoelectrics
  - Evaporative

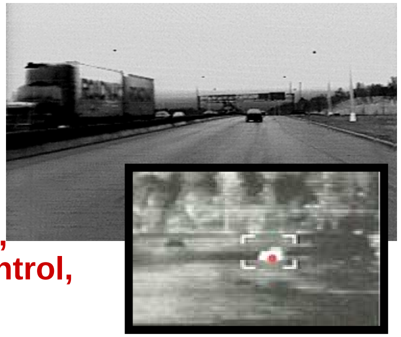
Fuel Cells

Micro-Turbines



Displays, Detectors, and Antennas

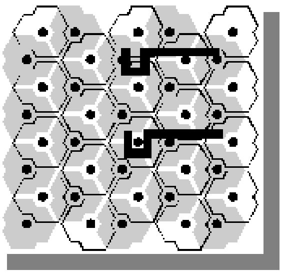
- **Displays**
  - Eye, Face, Sleeve, NV
- **Detectors**
  - Sensor fusion at focal plane
  - Wide angle and spectral coverage
  - Polarization and coherence sensitivity
- **Antennas**
  - Conformal, Low signature
  - Broadband / Multiband
  - Electronically reconfigurable
  - Low power consumption



Uncooled Thermal, Integrated Fire Control, Target Tracker & Laser Steering

Face-covering Display

Miniature Antennas on High Impedance Ground Plane



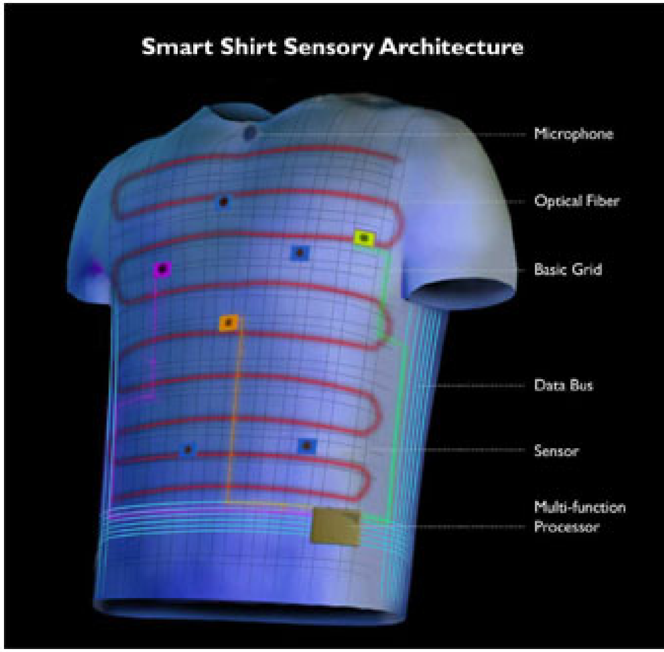
Soldier Status Monitoring and Modeling

Army Research Office

- Monitor Soldier Status
- Predict Performance
- Enhance Performance
  - Molecular internal computer
  - Sensory and mechanical enhancement
  - Active water reclamation
- Minimize Casualties
  - Local area monitoring
  - Clinical lab and pharmacy on the soldier
  - Regeneration/self healing
- Communications

Vital Signs Monitoring

Smart T-Shirt



Institute for Soldier Nanotechnologies

- **Technical**
  - **Emphasis on nano-materials research for protection**
    - Soldier protection from
      - Ballistics
      - Sensory attack
      - Chem/bio agents
    - Passively cool & insulate
    - Environmental adaptability
    - Biomedical monitoring
  - **Practical solutions**
    - Integrated solution suite
      - Rugged & synergistic
      - Compatible with sensors, comm, and power sources
    - World-class foundry of nano-materials synthesis

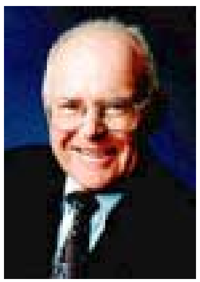
- **Programmatic**
  - **Single university host**
    - A "Mecca" of innovation
      - $10M/yr, 6.1 UARC, > 5 yrs
      - Dedicated facility
      - Cost & resource sharing
  - **Industrial partner(s)**
    - Integrate research solutions
      - Cost sharing required
      - Many commercial spin-offs
    - Army 6.2 funding likely
  - **More information**
    - http://www.aro.army.mil
    - Solicitation open now
      - Proposals due Jan. 3
      - Winner announced Apr. '02

Quantum Information Science

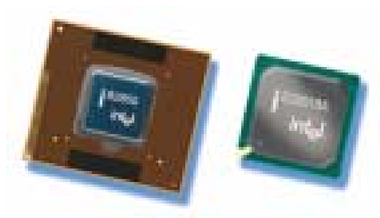
Quantum Information Science
in the Army

Nanoelectronics

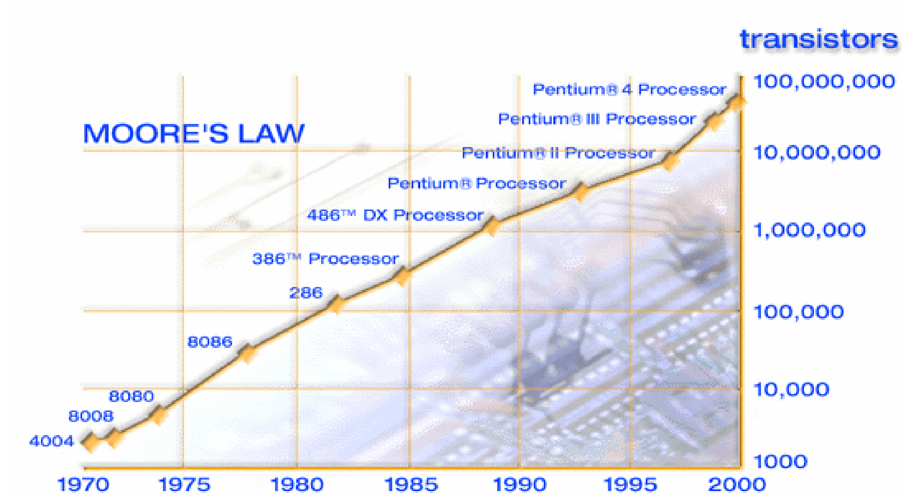
- **Moore's Law**
  - **Device sizes halve every 3 years**



    - US technological advantage is due in part to Moore's law
    - Pentium IV feature sizes 150 nm



- **Problem for Army**
  - **By Moore's law, devices should reach atomic scale by 2025**
    - Quantum effects will end Moore's law in 10-15 years
  - **US will lose technological advantage over adversaries soon after Moore's law ends**

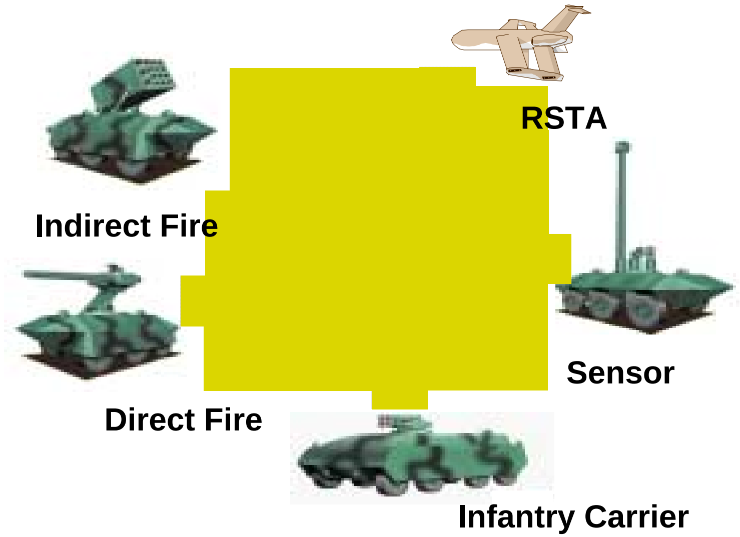


Hawk
Technology from 50's

Patriot
Technology from 70's

Information Age

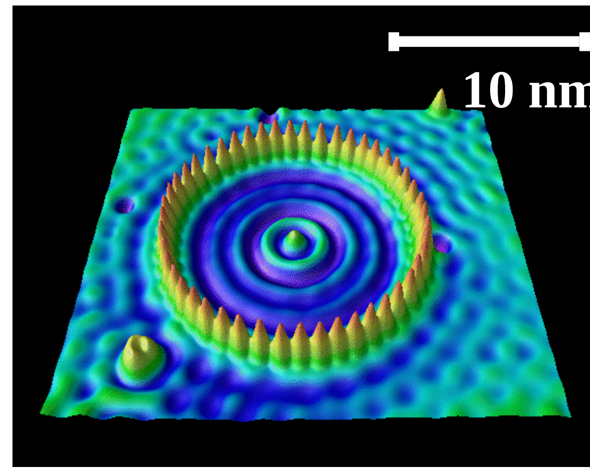
- **Digitization of the Battlefield**
  - **Major emphasis of the Army**
    - Increase situational awareness
    - Coordinate fire
    - Exploit rapid bandwidth growth
- **Problems for the Army**
  - **Mobile platforms**
    - Moving “cells”
    - Co-site interference
    - Free space vs line-of-sight
  - **Vulnerability to attack**
    - Nodal nature very vulnerable
    - Virulent viruses and worms
  - **Public key encryption**
    - Very successful
    - Intercepted messages take a long time to decipher



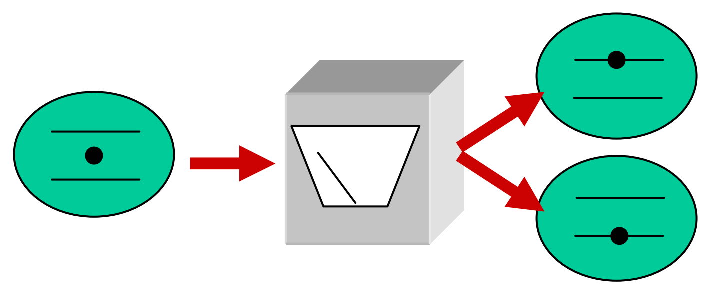
Quantum Information Science

- **Quantum Mechanics**
  - **. . . is weird!**
    - Particles act like waves
    - Particles tunnel through "impenetrable" barriers
    - Particles can be in two states at once
    - Entangled particles are correlated at all times
- **Quantum Info. Science**
  - **Quantum computers**
    - Solve problems classical computers can't
  - **Quantum communication**
    - Security guaranteed by quantum mechanics

Electron Waves



Superposition and Measurement



Quantum Communications

Quantum Information Science
in the Army

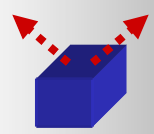
Quantum Cryptography

Army Research Office

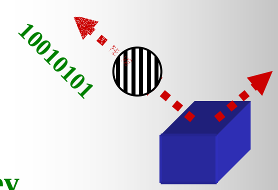
Quantum Key Generation

How it works

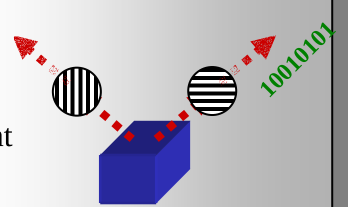
Step 1: Alice and Bob start.
Polarization entangled photon pairs are generated.



Step 2: Alice sets key.
Alice measures polarization of **one entangled photon**. Result of measurement is **key**.



Step 3: Bob reads key.
Alice tells Bob what measurement she made. Bob gets **key**.



Step 4: Message sent.
Alice encodes message and sends it to Bob through open channels. Bob decodes message.

- **Cryptographic keys**
  - Q entanglement allows random key to be shared by two users
  - Encoded message sent through open channels
  - Working systems exist now
    - >40 km in fiber
    - ~1 km in free space
    - Earth-to-satellite system being developed at LANL
- **Security**
  - QM:
    - **Key is unbreakable: it cannot be copied!**
  - Eavesdropper would destroy key by trying to read it.

Quantum Communication

Army Research Office

- **Quantum Teleportation**
  - Quantum entanglement can be used to teleport message
  - Quantum teleportation proven!
    - Demonstrated in 3 labs in ‘98.
    - Army/DARPA initiative to develop Q network underway.
- **Security**
  - Message never travels between Alice and Bob
    - A need not know where B is
  - Alice sends activation signal to receiver (selected availability)
    - Alice’s copy destroyed when teleported

Quantum Teleportation

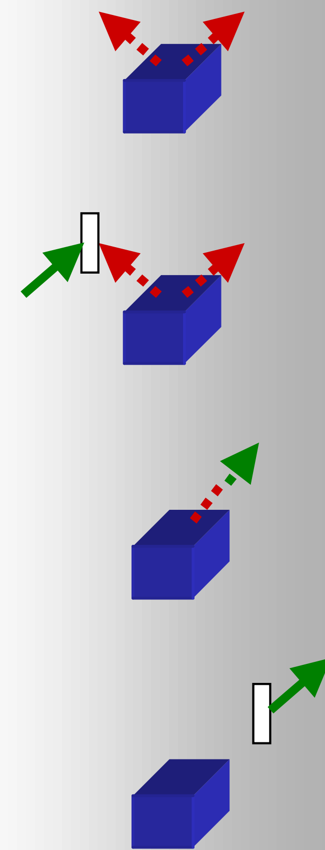
How it works

Step 1: Alice and Bob start.
Polarization entangled photon pairs are generated.

Step 2: Alice sends message.
Alice entangles **message photon** with **one entangled photon**.

Step 3: Bob receives message.
Alice’s **message** is destroyed as it is teleported to Bob on **second entangled photon**.

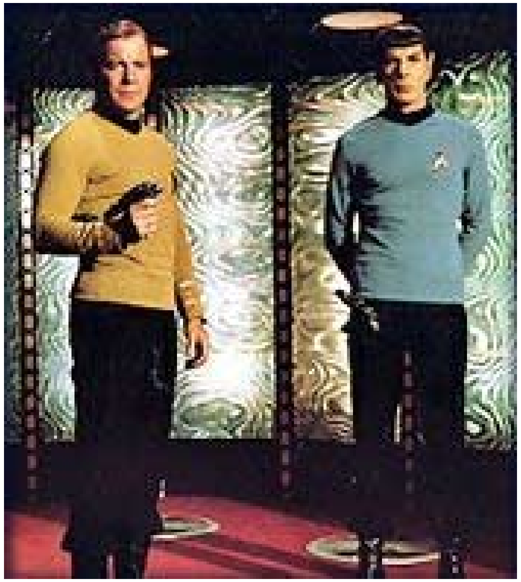
Step 4: Bob reads message
Alice tells Bob how to measure **second entangled photon** to read **message**.



Science Fiction vs Science Fact

Superluminal Effects

Matter Teleportation



Los Alamos Quantum Cryptography System

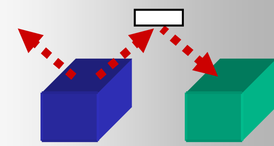
Quantum Teleportation Experiment

Quantum Memory

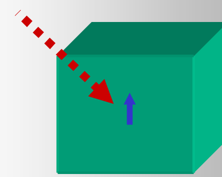
- **Coherence Transfer**
  - To store quantum information, it must be transformed from one form (easily transmitted) to another (well isolated)
- **Quantum Memory**
  - **Required for long range and random access Q comm.**
    - 100 km requires 1ms storage
    - Nuclear spin T_2 ~ hours
    - Secure or long range comm requires 1 day - 1 yr storage
  - **Enables tactical and strategic Q teleportation for secure comm.**

How it works

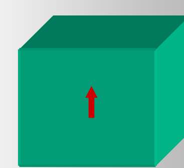
Step 1: Information received.
One photon of **entanglement** pair is received and ready for storage.



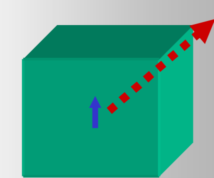
Step 2: Information stored.
Entanglement transferred from photon to, say, a nuclear spin.



Step 3: Information saved.
Coherence maintained naturally and/or through Q error correction.



Step 4: Information retrieved.
Entanglement transferred from spin to photon for immediate use.



Quantum Error Correction

- **Q Measurement**
  - **Q states are fragile, error prone**
  - **Measuring a Q state destroys the Q information**
- **Q Error Correction**
  - **Errors can be corrected without looking at Q state**
    - Errors detected using redundant storage and comparative measurement
    - Errors corrected using conditional logic and flips
  - **Error correction proven, but not enough to extend T_2 yet**

How it works

Vulnerable storage
Quantum state represented simply as **superposition**. Bit flip creates **error**.

a|0>+b|1>

a|1>+b|0>

Step 1: Redundant storage
Encode **Qbit** in state of **3 Qbits**

a|000>+b|111>

Step 2: Bit flip error occurs.

a|100>+b|011>

Step 3: Error detected.
Qbits compared to each other, 2 at a time, for discrepancies.

a|100>+b|011>

Step 4: Error corrected.
Comparative measurments reveal **error** on **Qbit 1**; **Qbit** flipped.

a|000>+b|111>

Quantum Error Correction

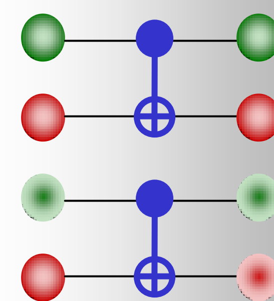
- **Quantum Logic**
  - **Whether target bit is flipped depends on control bit**
    - Control:0, Target: unflipped
    - Control:1, Target: flippped
  - **“Controlled-NOT”**
    - For comparison or conditional manipulation of Qbits
    - Universal Q gate
  - **Quantum logic demonstrated in atoms**
    - Solid state demos in < 3 yrs
    - Used for quantum repeaters
    - Key to quantum computation

How it works

Controlled Not

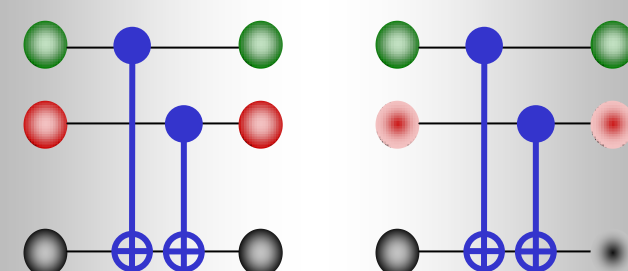
Target Qbit not flipped if **control Qbit** is 0.

Target Qbit flipped if **control Qbit** is 1.



Collective Measurement

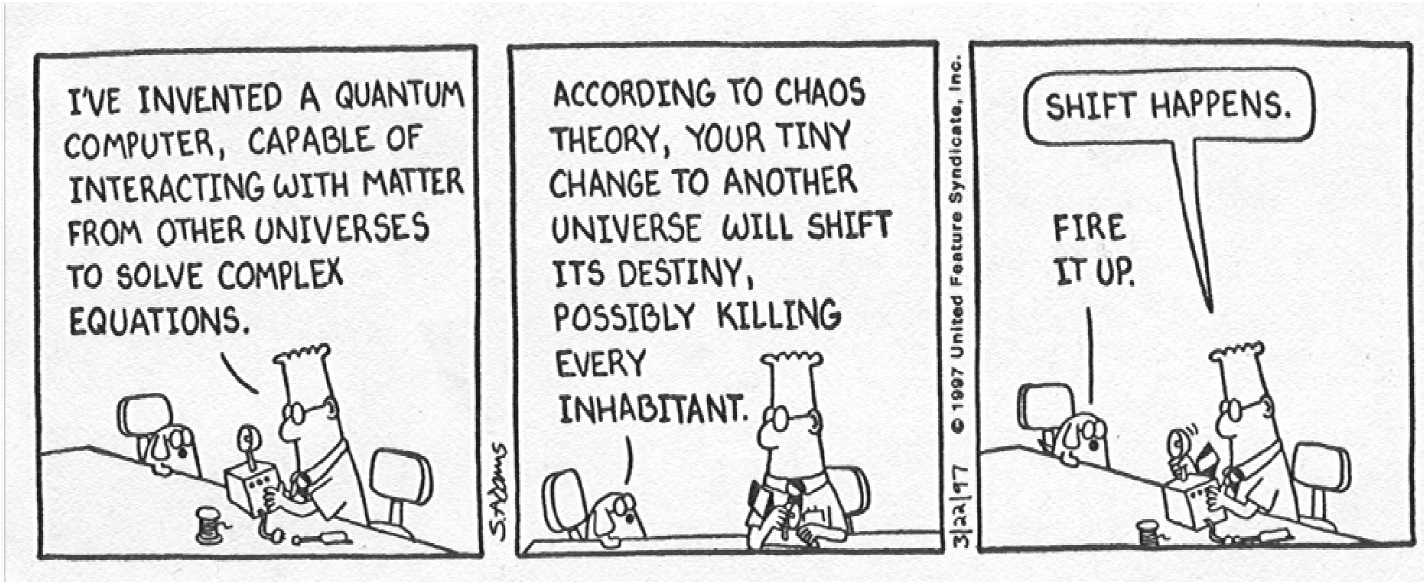
Qbits **A** and **B** are compared using two **C-NOTs** and a third “**ancilla**” bit



Quantum Computing

Quantum Information Science in the Army

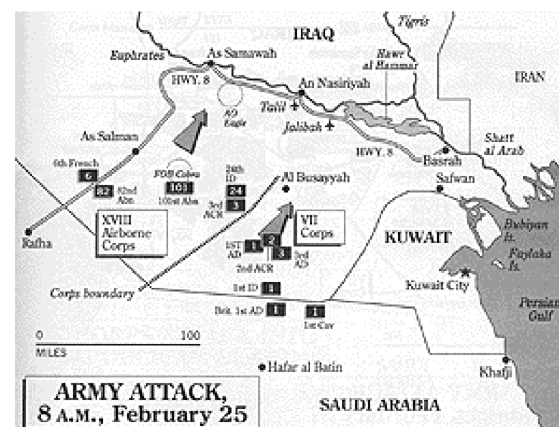
Why should we build a Quantum Computer?



Code Breaking

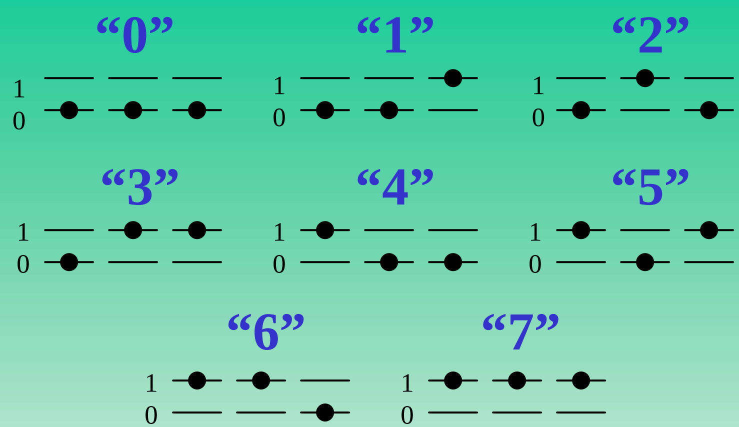
Resource Optimization

Wargaming, Logistics

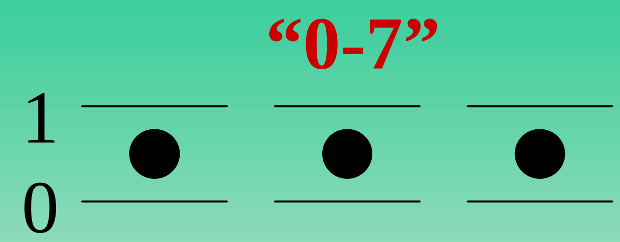


How a Quantum Computer Works

Army Research Office



- **Classical Computer**
  - **Classical bits must be either 0 or 1.**
  - **N bits represent any number [0, 2^N-1].**
  - **Loop over all numbers in 2^N operations.**



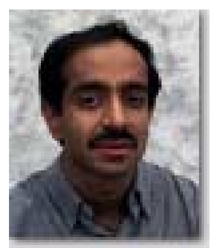
- **Quantum Computer**
  - **Superposition allows Qbits to be between 0 and 1.**
  - **N Qbits represent all of [0, 2^N-1] *simultaneously*.**
  - **Loop over all numbers in 1 operation.**

Quantum Computation

- **Shor's Code-breaking Algorithm**

  - How fast can you factor a number?
    - Difficulty grows exponentially with number of digits
  - Q computer advantage
    - Code-breaking can be done in minutes, not millennia

- **Grover's Search Algorithm**



  - How quickly can you find a needle in a haystack?
    - Difficulty grows exponentially with number of items (N)
  - Q computer advantage
    - Search 10^6 items 500X faster

- **How public key cryptography works**
  - Multiplying two prime numbers is easy
    - 23 x 47 = ?
  - Factoring a number into its two prime cofactors is hard
    - 1961 = ? x ?
  - If N-digit key can be factored, increase N to increase security

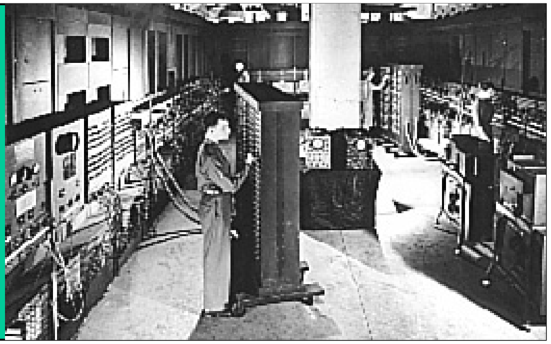
- **Classical Search**
  - Sequentially try all N possibilities
  - Average search takes
    - N/2 steps
- **Quantum Search**
  - Simultaneously try all N possibilities
  - Refining process reveals answer
  - Average search takes
    - $N^{1/2}$ steps

Why is it hard to build a quantum computer?

- **Quantum states are fragile.**
  - Noise causes errors, and state preparation is imprecise.
  - Quantum error correction will help.
- **Few algorithms exist.**
  - Readout of quantum states yields probabilistic answer.
- **Seven qubit quantum computers are operating now.**
  - Researchers may need 20 years to build a QC that will solve important problems (>1000 qubits).

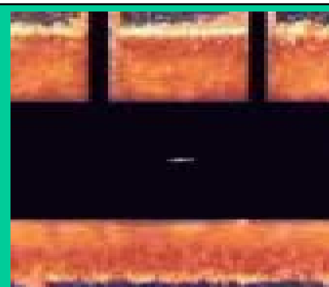
"Where a calculator on the Eniac is equipped with 18000 vacuum tubes and weighs 30 tons, computers in the future may have only 1000 tubes and weigh only 1 1/2 tons"

- Popular Mechanics, March 1949

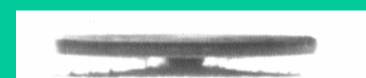


Physical Implementations

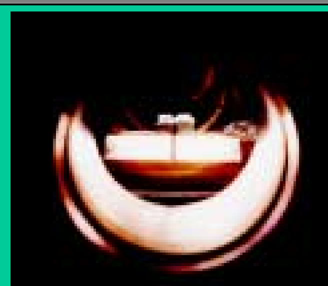
Ion Traps



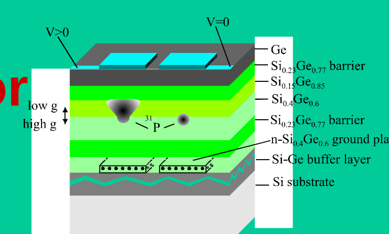
Semiconductor Q Dots



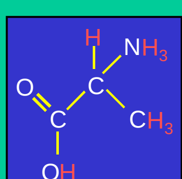
Atom Traps

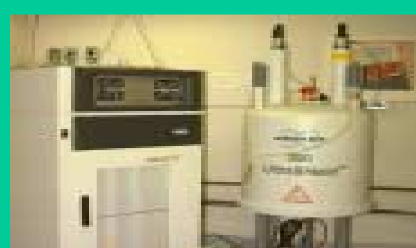


Semiconductor Spins

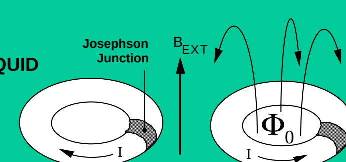


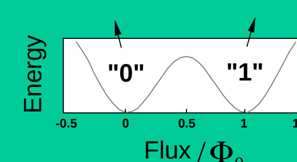
NMR





Superconductors





Summary

- **Nanotechnology**
  - **Photonic Band Engineering**
    - Compact photonics
    - Efficient antennas
  - **Chemical and Biological Agent Detection**
  - **Soldier Nanoscience**
    - Advanced Uniform & Devices
    - Survivability & Sustainability
- **Quantum Information**
  - **Quantum Communication**
    - Secure communication
  - **Quantum Computing**
    - Computing after Moore's law
    - Code breaking