

The Quantum Computing Company™

Technology Demonstration

Computer History Museum

Mountain View, CA February 13th 2007

Herbert J. Martin
Chief Executive Officer

The Prologue

The advent of the D-Wave quantum computer does not signal the end of digital computing;

nor does it signal the beginning of the end.

It does, however, mark the end of the beginning of quantum computing.

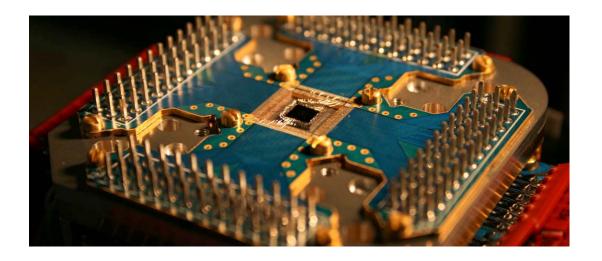


Digital Computers have Limitations

- Moore's Law forecasts a collision between the microprocessor and the laws of physics, but the industry will adapt
- Continuing Moore's Law advances insufficient to solve certain high-value problems
- The D-Wave system provides an exciting acceleration alternative for solving problems beyond the scope of digital computers



What is a D-Wave Quantum Computer?

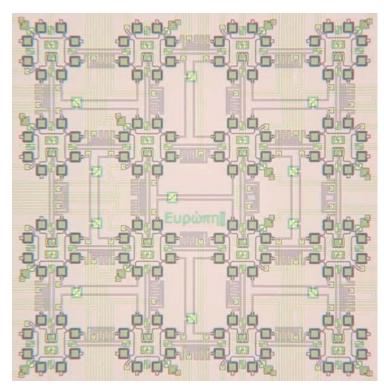


- Adiabatic Quantum Computer
- Employs superconducting magnetic flux qubits
- Accelerator for existing applications and solving problems previously considered intractable
- Naturally parallel but logically serial architecture
- Compelling cost of ownership and eminently scalable □:₩2VC

The Quantum Computing Company™

The Heart of the System — is it scalable?

- Fabricated using industry standard semiconductor equipment and processes
- Array of superconducting flux qubits
- Cooled to 4 mK in liquid helium
- Requirements well within industry state-of-the-art
- We benefit from semiconductor fab advances





How Does it Work?

- Leverages quantum mechanical effects to compute
- A problem is presented as a graph to the quantum hardware
- The system obeys the laws of quantum mechanics and settles to its lowest energy state
- This is the solution to the problem which is then read and passed to the software



What Applications is it Useful For?

Bio Science

- Genomics
- Lattice protein folding

Chemistry

- Quantum simulation
- Drug discovery

• CAD/CAE

Electronic CAD (Place and Route)

Finance / Economics

- Quantitative Finance
- Market segmentation/cluster analysis

Security

- Parametric pattern searching in large database structures
- Biometrics

Operations Research

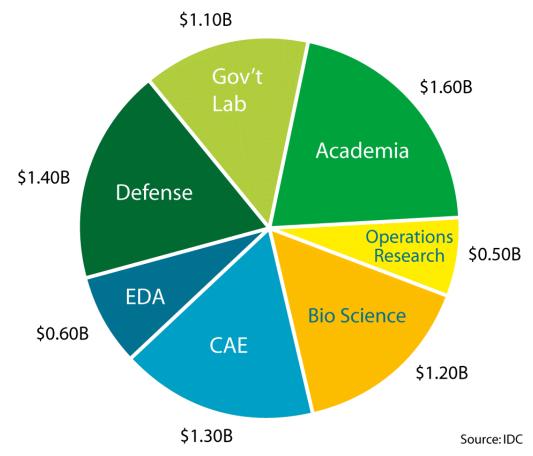
- Logistics
- Inventory management
- Optimization
- Supply Chain optimization
- Complex product configuration
- Knowledge management
- Project scheduling

Search

- Enterprise search
- Intellectual Property (IP) search
- Web search (automotive, personals)
- Mobile device search



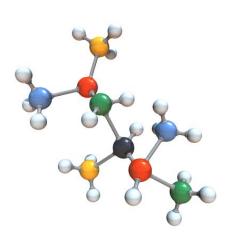
Large Market Segments



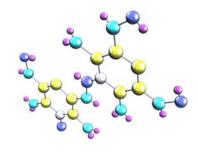


D-Wave's Addressable Market is Broad!!!

The HPC market consists of multiple Billion Dollar verticals



Totals in Thousands	2005
Bio-Sciences	\$1,198,416
CAE	\$1,296,509
Chemical Engineering	\$310,197
DCC & Distribution	\$144,105
Economics/Financial	\$317,344
EDA	\$631,773
Geosciences and Geo-engineering	\$306,423
Mechanical Design and Drafting	\$181,000
Defense	\$1,371,911
Government Lab	\$1,141,305
Software Engineering	\$25,901
Technical Management	\$305,883
University/Academic	\$1,653,557
Weather	\$291,904
Other	\$21,792
Total Revenue	\$9,198,020



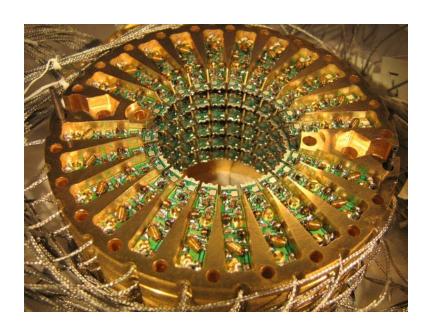


Source: IDC, 2006



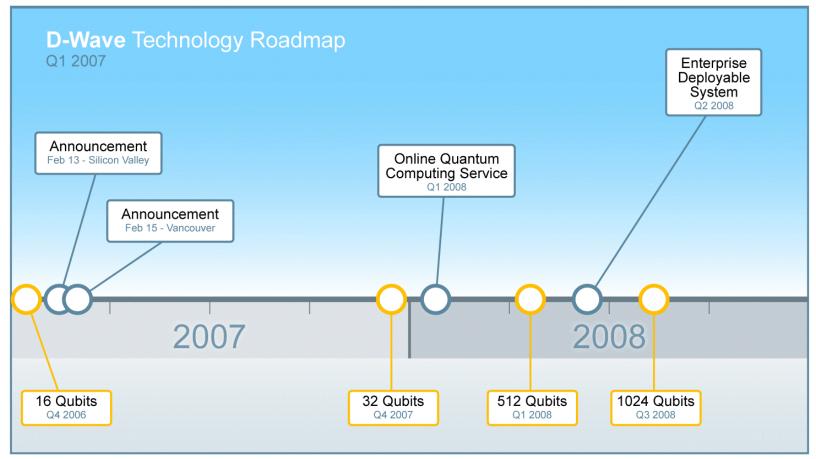
D-Wave Today

- A scalable architecture
- Working 16 qubit system
- Quantum based applications development platform
- Reference design for parametric search application with preference engine
- Patents: 100 filings worldwide,
 US 35 issued, 29 pending
- Strong near term roadmap to a commercially deployable system





Major Milestones





Epilogue

The D-Wave quantum computer system will herald a new age of computing where nature is harnessed to provide fast accurate solutions to problems previously classed as intractable

By enabling new applications and scaling old the system will create demand for trillions of additional digital computing cycles thereby growing the market for digital computers.



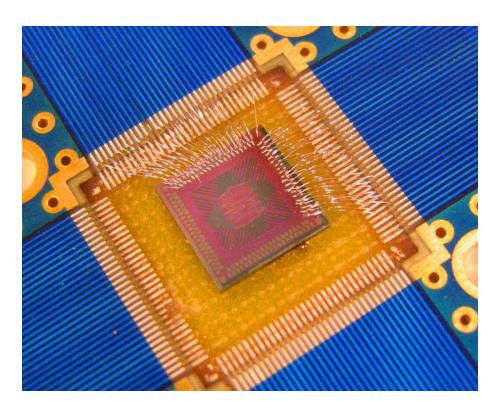
Thank You

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http://www.dwavesys.com

info@dwavesys.com







Technology Overview and Demonstration

Computer History Museum

Mountain View, CA

February 13th, 2007

Dr Geordie RoseFounder and Chief Technology Officer

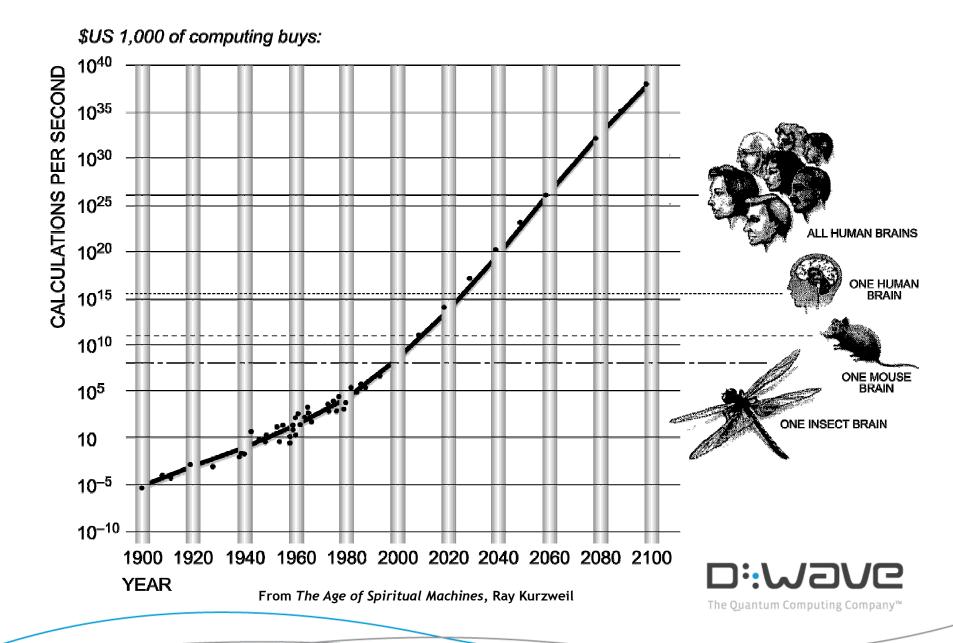
The IBM 350

- 1956—the first hard disk drive
- 4.4 MB of storage
- Weighed over a ton
- About 1,000 systems built



Image from www.ichigo.se/noterat/wp-content; information from http://en.wikipedia.org/wiki/RAMAC

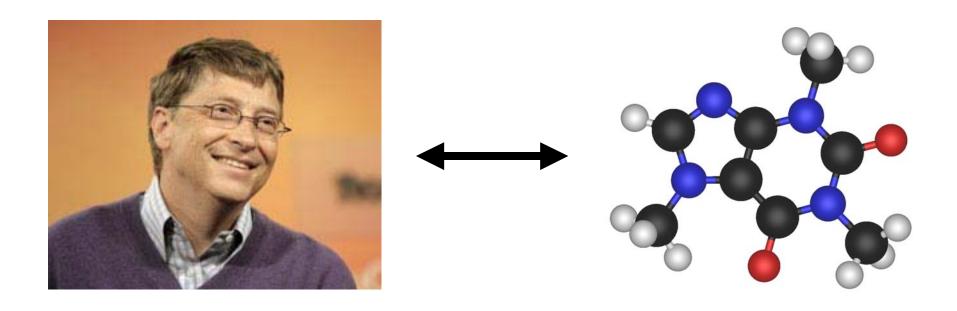




At key points in human history, civilization took a leap forward because people discovered a new way of exploiting nature. Toolmaking, farming, the industrial revolution, and the information revolution were all triggered by the discoveries of new ways of manipulating nature. Quantum computation... could turn out to be as significant in its effects on human civilization.

Julian Brown
The Quest for the Quantum Computer





We are stardust, we are golden // We are billion year old carbon

Woodstock, Joni Mitchell

Bill Gates image from www.microsoft.com



The fundamental laws necessary for the mathematical treatment of large parts of physics and the whole of chemistry are thus fully known, and the difficulty lies only in the fact that application of these laws leads to equations that are too complex to be solved.

Paul Dirac Nobel Prize winner, 1929



Nanotechnology is projected to be a \$1 trillion market by 2015.

Government Nanotechnology Funding: An International Outlook
National Science Foundation, June 30, 2003

Eventually, it has been estimated that we will be able to build just about anything for a dollar a pound, no matter what it is, whether a supercomputer or structural elements.

Steve Jurvetson

The Next Material World, Industry Week 4.1.2003



Overview

- What Orion does
- Under the hood: The quantum processor
- The demo
- A vision for the future



What Orion does

- You've got data
- Extracting information can be extremely time consuming
- Orion is designed to dramatically accelerate a general class of queries
- No changes needed to your data format or your programming language



Here's an example

```
MySQL Command Line Client
Enter password: ********
Welcome to the MySQL monitor. Commands end with ; or \g.
Your MySQL connection id is 11 to server version: 5.0.24a-community-nt
Type 'help;' or '\h' for help. Type '\c' to clear the buffer.
mysql> use calvin_db;
Database changed
mysgl> select * from RoadsInSweden;
 CITY FROM ! CITY TO
                           I DISTANCE KM
 Stockholm ! Gothenburg
                                   511.8
 Stockholm | Malmo
 Stockholm | Helsingborg |
                                   484.3
 Gothenburg | Malmo
                                   242.6
 Gothenburg | Helsingburg |
             | Helsingburg |
 Malmo
 rows in set (0.00 sec)
mysq1>
```



Bring the pain: Some queries are (really) hard!

 Find the optimal tour of 24,978 cities in Sweden (Traveling Salesman Problem)

85 years for a fast PC





From http://www.tsp.gatech.edu/sweden/index.html

The math behind this particular pain

- Problem underlying target queries: integer programming
- AKA discrete optimization
- AKA NP-complete / NP-hard



Where the hard queries are

All sorts of places:

- Semiconductors: Chip design & optimization
- Bioinformatics: Protein folding, pattern matching
- Logistics: Planning, staffing, shipping, scheduling, routing
- Finance: Capital budgeting & investment planning
- Entertainment: Games
- Communication: Spectrum allocation, network design
- Security: Biometrics, motif & fraud detection
- Parametric search: Personals, autos, IP and
- other enterprise search

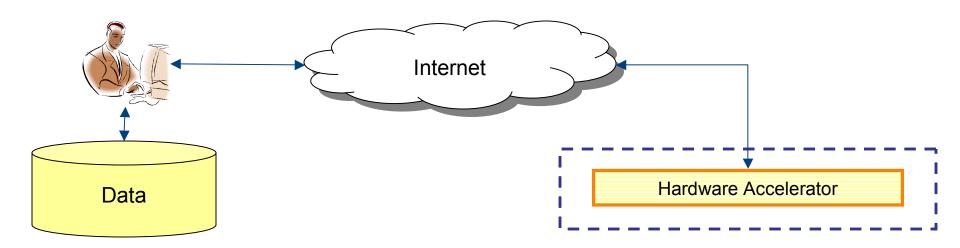


How to use Orion

- Program in SQL
- Hard queries solved via hardware acceleration



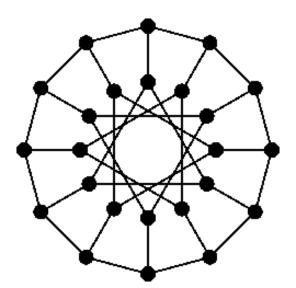
High-level systems architecture





A simple example: Find a property of a graph

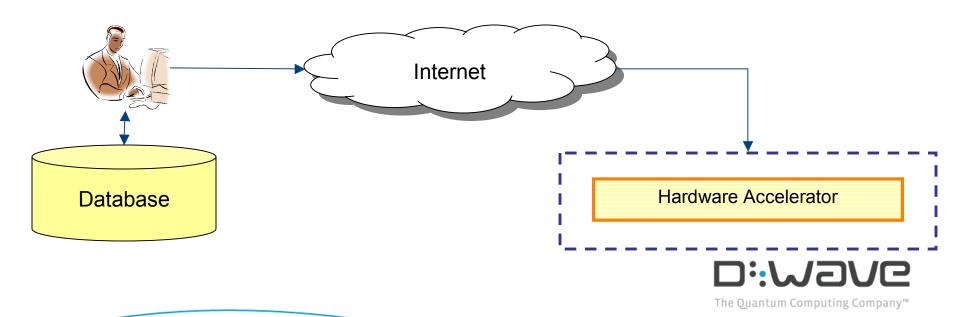
- A graph is a table of vertices and edges
- The Maximum Independent Set (MIS) is the largest subset of vertices such that no two vertices in the subset share an edge

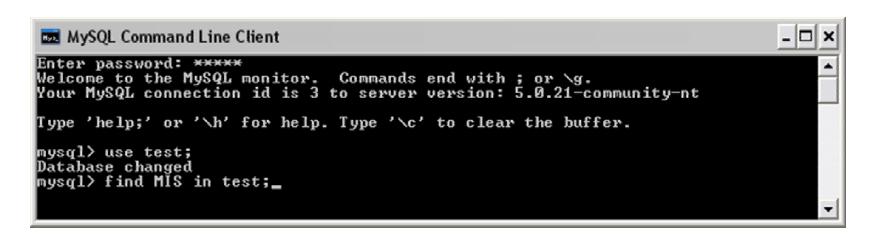


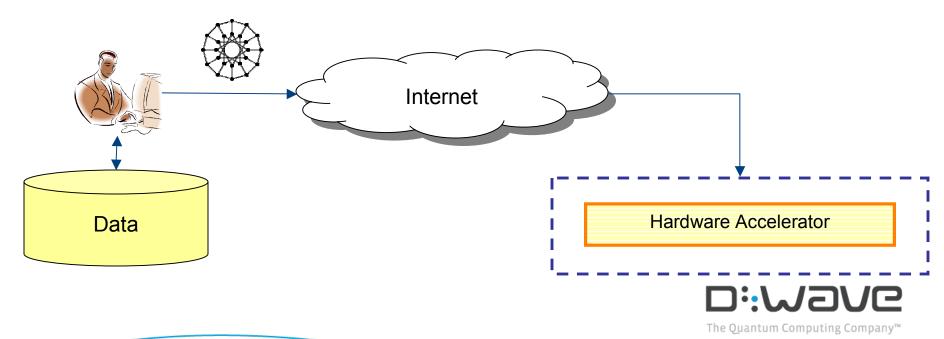
From http://en.wikipedia.org/wiki/Independent_set; original image by Claudio Rocchini



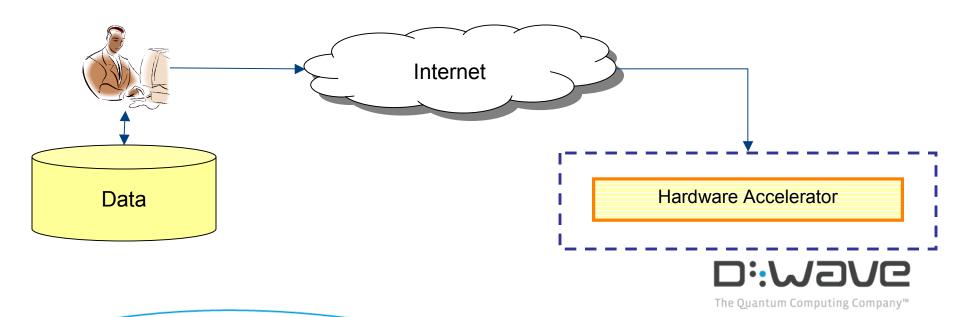


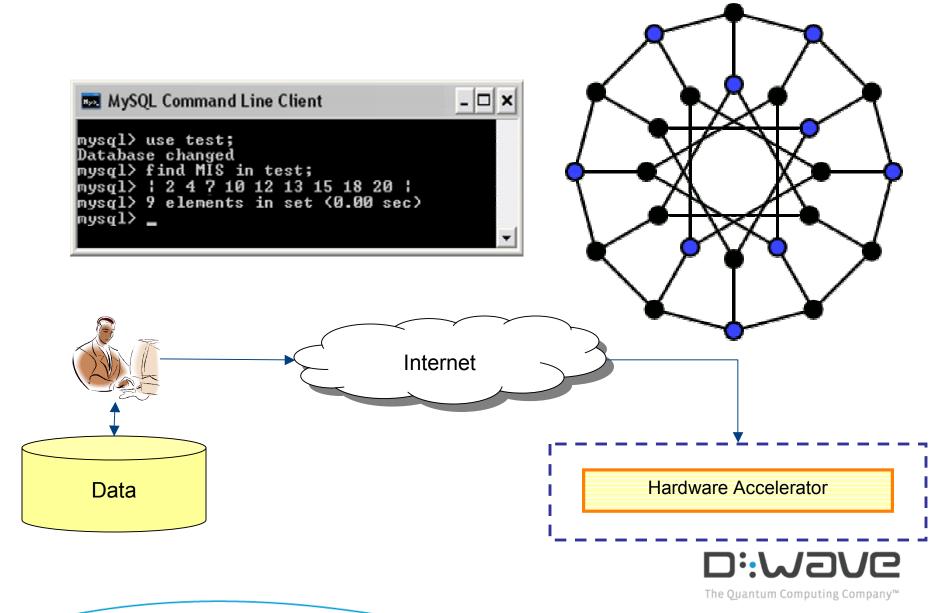












Under the Hood:

The quantum processor

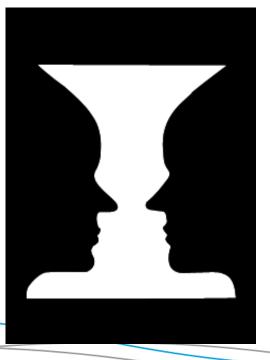


A problem with a split personality

 Query reduced to an integer program, AKA the two-dimensional Ising model in a magnetic field (2DIMM) problem

This integer program is what the hardware accelerator receives

as input



Rubin face/vase picture from http://www.jyi.org/volumes/volume10/issu e4/articles/dilkina.html



What this means to a computer scientist

• Integer programming is NP-complete

Even many computer scientists do not seem to appreciate how different the world would be if we could solve NP-complete problems efficiently... If such a procedure existed... we could make an easy fortune on Wall Street, or retrace evolution, or even generate Shakespeare's 38th play.

Scott Aaronson
NP-complete Problems and Physical Reality
ACM SIGACT News, March 2005



What NP means

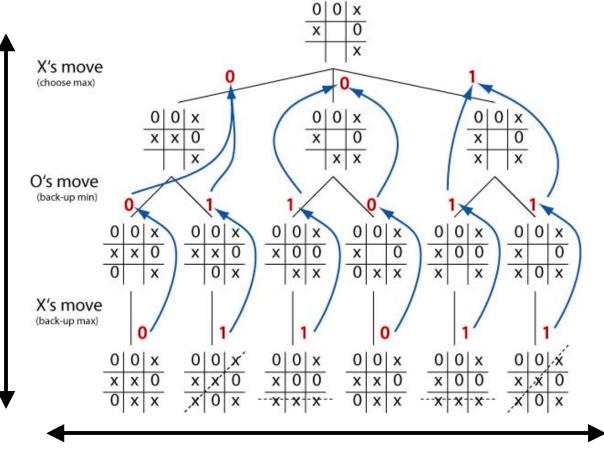
- Computational Complexity:
 - As the size of the input to an algorithm increases, how do the running time and memory requirements of the algorithm change?
- NP: "Non-deterministic polynomial time"
- Decision problems (yes/no)



An Example

• Can O win?

No worse than a polynomial of the problem size (Na)



No worse than an exponential of the problem size (A^N)

NP-complete & NP-hard

- NP-complete are hardest problems in NP
- No known algorithm can efficiently solve NP-complete problems
- NP-hard can be thought of as optimization versions of NP-complete decision problems



What this means to a physicist

Model for describing real physical systems

The Ising model tries to imitate behaviour in which individual elements (e.g., atoms, animals, protein folds, biological membrane, social behavior, etc.) modify their behavior so as to conform to the behavior of other individuals in their vicinity... More than 12,000 papers have been published between 1969 and 1997 using the Ising model.

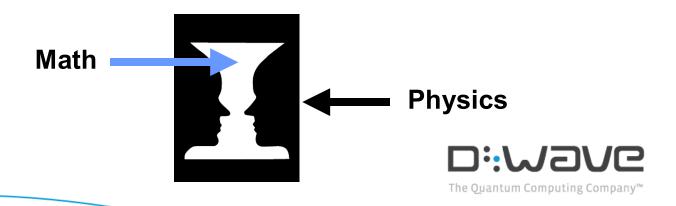
http://scienceworld.wolfram.com/physics/IsingModel.html



Core concept: Use (quantum) physics to do math

 Deep connection between hard math problem and fundamental laws of nature

 Build an "analog computer" at the ultimate limits of what is possible... any computer that could do better would violate the laws of physics



In the digital approach, you first devise an algorithm (a set of instructions for finding the solution to a problem), then execute each step of the algorithm in the manner of Boolean operation. In contrast, analog computation is concerned with no symbolic Boolean operation; instead it utilizes the properties of a physical system to perform the mathematical operations required for the solution.

Tokuda et.al.
Analog Computation Using Single-Electron Circuits
Analog Integrated Circuits and Signal Processing, June 2000

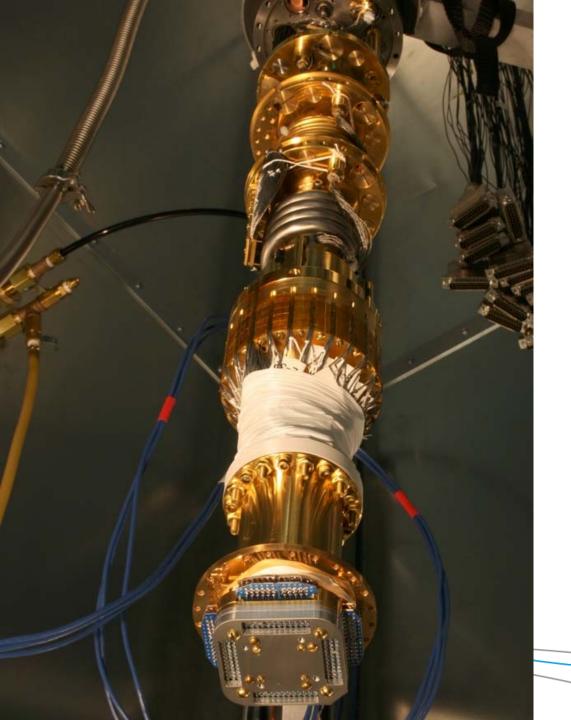


Our approach: Superconducting adiabatic quantum computer

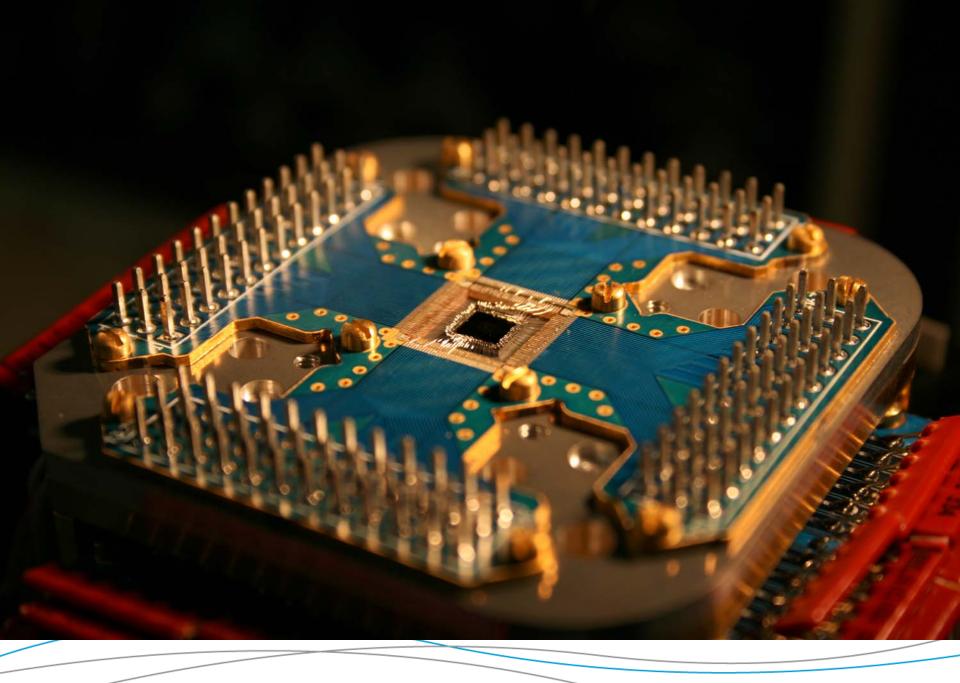
- Extremely fast: Special purpose processors can be orders of magnitude faster than general purpose processors, and superconducting electronics are naturally fast
- Extremely low power: Power consumption & heat generation drastically reduced (factors of thousands)
- At the limits of physics: Solving problems requires "fewer steps"... can't do better

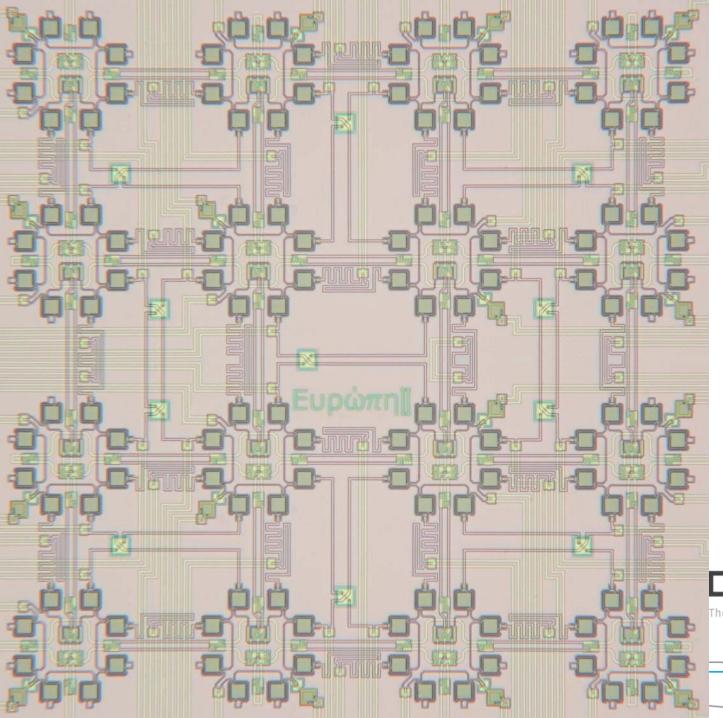














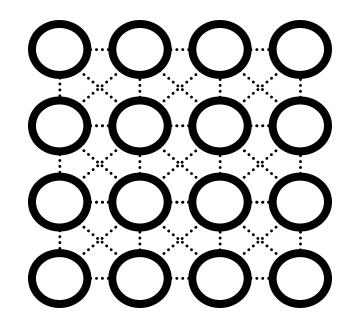
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How Does it Work?



Build the (quantum) physical embodiment of a class of hard math problems

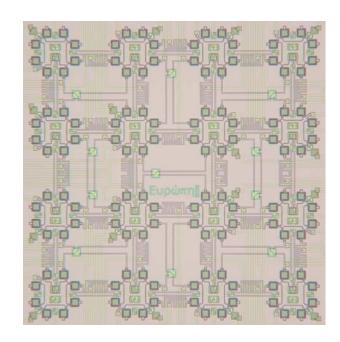
- Chip programmed by setting numbers on vertices and edges of real hardware array
- After calculation qubit values are read out; the lower the energy of the system, the more accurate the answer is





Build the (quantum) physical embodiment of a class of hard math problems

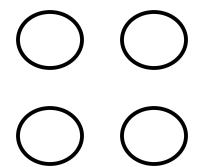
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More specifically...

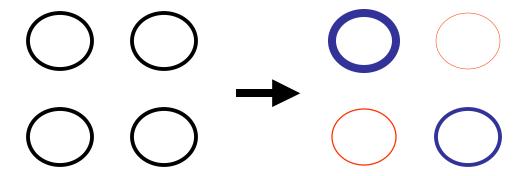
Given a program $\{h_i, J_{ij}\}$, output a solution $\{s_i=\pm 1\}$ that minimizes $E(s_1,...,s_N) = \sum_{ij} J_{ij} s_i s_j + \sum_i h_i s_i$





Numbers on vertices

h_i are *local biases*: Blue favors -1, red favors +1



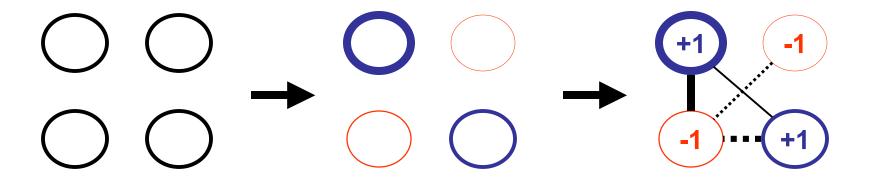


Numbers on edges

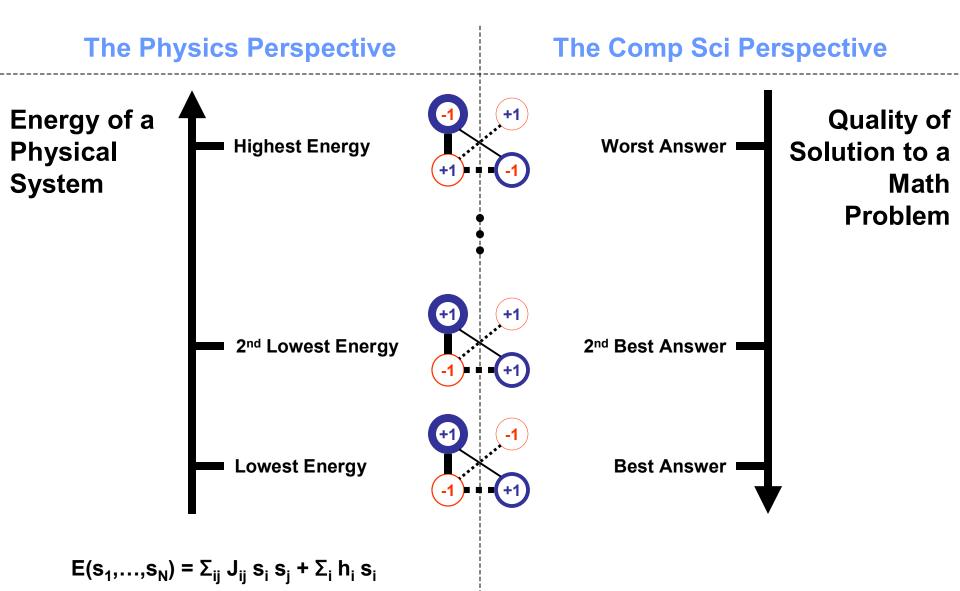
J_{ii} are *coupling strengths*: solid →like, dashed →opposite

What solutions look like

A solution is a configuration of variables $\{s_i\}$; the optimal solution is the configuration $\{s_i\}$ that minimizes E



Lower energy = more accurate solution



QM helps the computer find the best answer

- Can think of quantum effects as providing many more possible paths "down the hill" to the lowest energy solution
- AQC is as powerful as QC gets
- Our approach is the "shotgun sequencing" of QC



The Demo



Application Zero: Establish connection with QC



Application #1: Structure Search



Exponential Data Explosion

• PubChem:

- 15,460,039 chemical structures

Sequences (milllons)

GenBank:

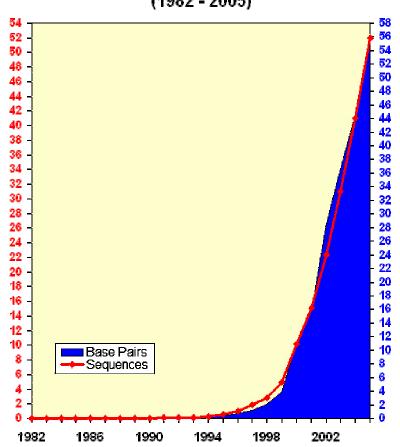
- 65,369,091,950 bases in 61,132,599 records

Protein Data Bank:

— 29,937 structures

Growth of GenBank

(1982 - 2005)



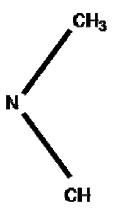
From http://www.ncbi.nlm.nih.gov/Genbank/genbankstats.html

Database: DrugBank

- http://redpoll.pharmacy.ualberta.ca/drugbank/
- "The DrugBank database is a unique bioinformatics and cheminformatics resource that combines detailed drug (i.e. chemical, pharmacological and pharmaceutical) data with comprehensive drug target (i.e. sequence, structure, and pathway) information."
- ChemQuery: Search DrugBank for compounds similar to a query compound



Query Compound

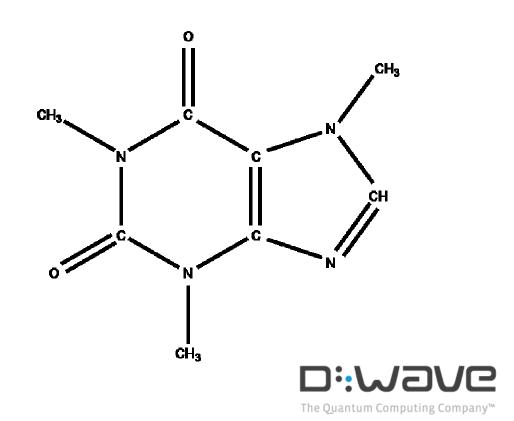


Molecule pictures from http://www.cs.virginia.edu/~an4m/T-shirt/



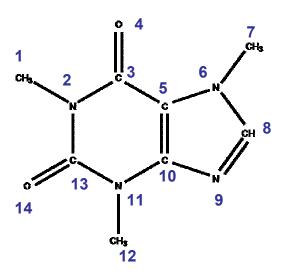
Database Molecules

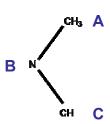
• Example: Caffeine



The Pattern Matching Compiler

Database & query objects converted into labeled graphs

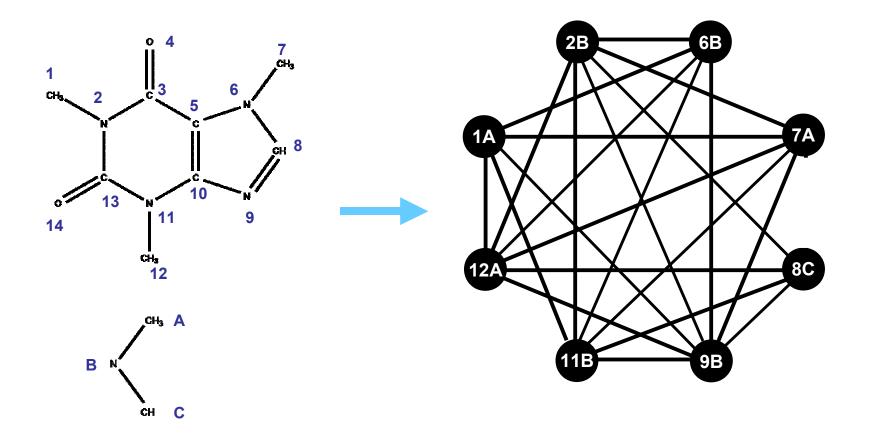


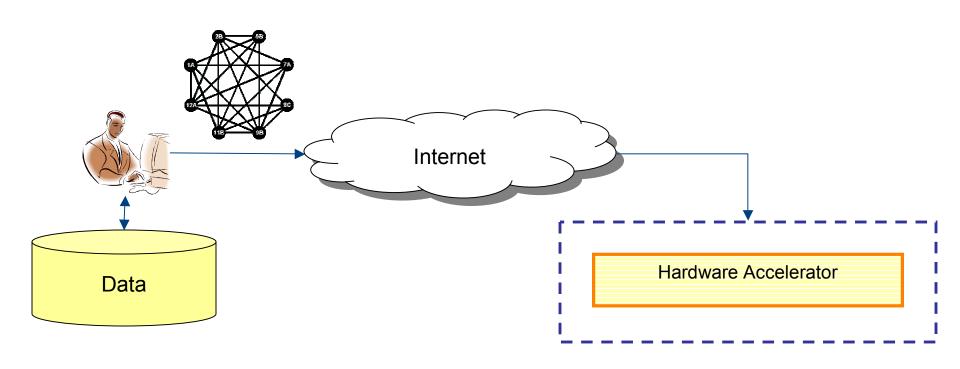




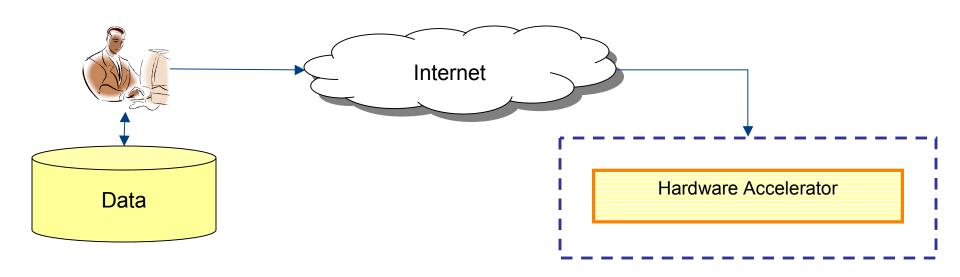
The Pattern Matching Compiler

Build *Association Graph:* one vertex per pair of perfect vertex label matches; edge if no relations between pairs hold

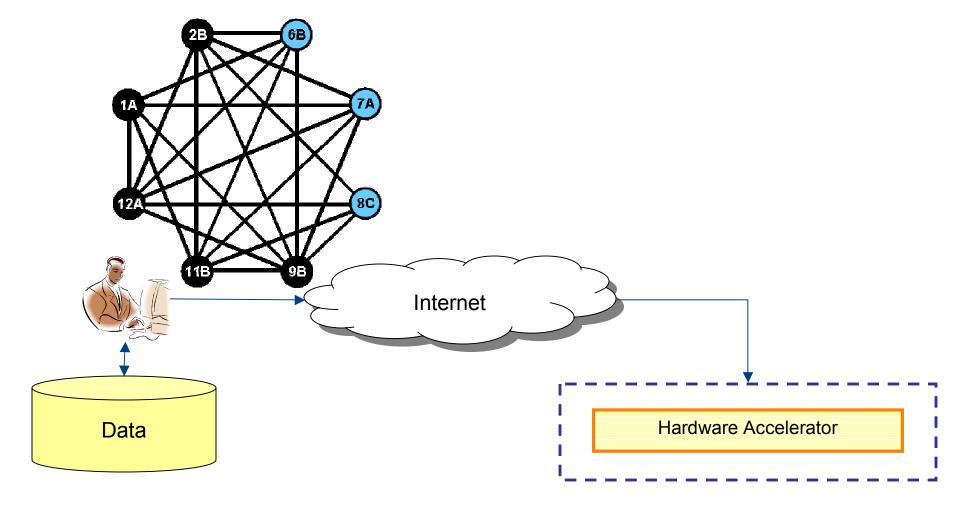






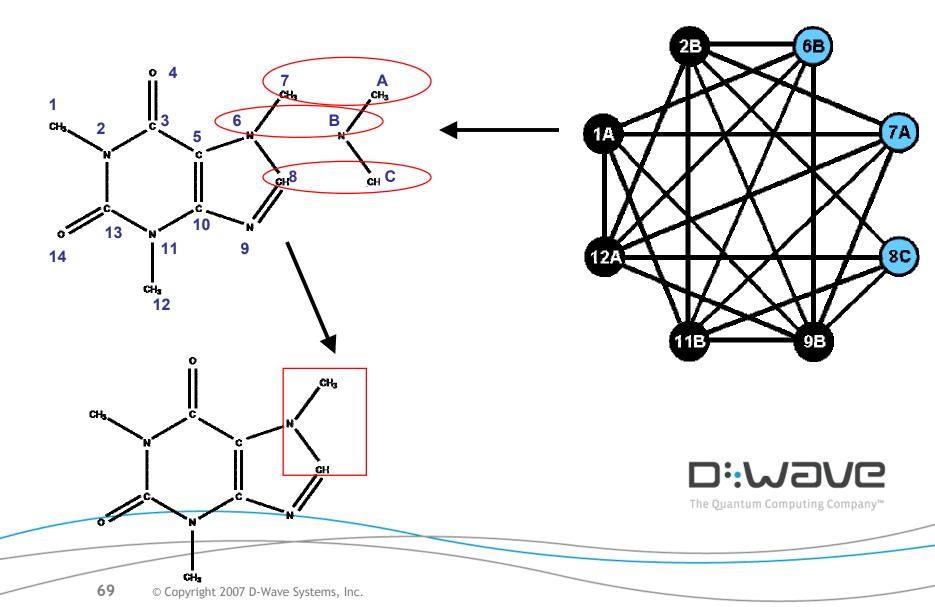








Output {8C, 7A, 6B} is area of maximal overlap



Application #2: Constraint Satisfaction



Third-Party Applications Easy to Port

- PerfectTablePlan from Oryx Digital Ltd.
- Assigns people to seats subject to their preferences
- Can be purchased from www.perfecttableplan.com



Application #3: Games



SudoQ

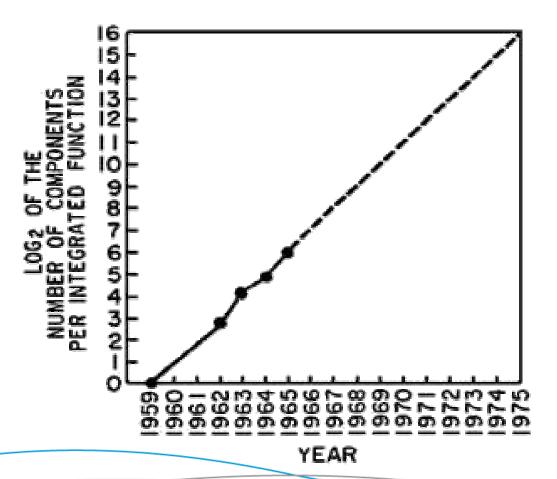
- Some puzzles & game components are NP-complete
- Applications in game Al (decision making, eg. path finding)
- SudoQ solves Sudoku problems



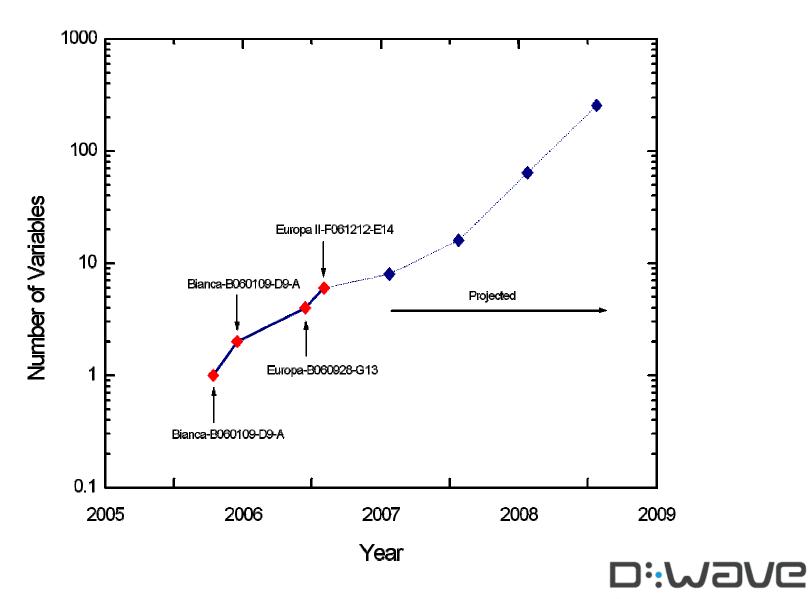
A vision for the future

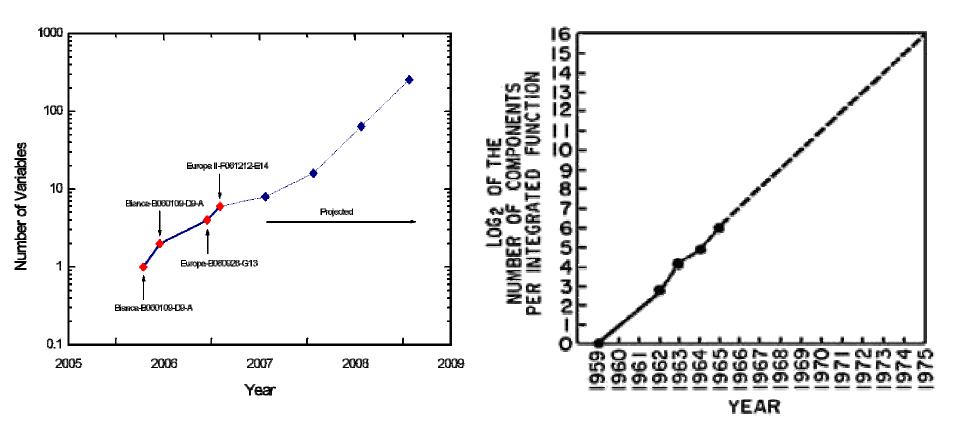


"Integrated circuits will lead to such wonders as home computers — or at least terminals connected to a central computer, automatic controls for automobiles, and personal portable communications equipment."











We meet at a college noted for knowledge, in a city noted for progress, in a state noted for strength, and we stand in need of all three, for we meet in an hour of change and challenge, in a decade of hope and fear, in an age of both knowledge and ignorance. The greater our knowledge increases, the greater our ignorance unfolds... the vast stretches of the unknown and the unanswered and the unfinished still far outstrip our collective comprehension.

John F. Kennedy September 12 1962

