DELIVERABLE D1.3.1

ORGANIZATION OF A SPECIAL INDUSTRY SESSION AT A BIG QIPC CONFERENCE

In 2011, one of the two big international conferences initiated by QUIE²T was organized. The QIPC 2011 Conference[1] was held at ETH Zürich from September 5 - 9, 2011. The conference program included 32 invited talks, 70 contributed talks and more than 100 poster presentations covering a broad range of topics. As such, the conference was one of the biggest QIPC events of the year in Europe.

A report was assembled right after the conference that was used by the local organizers as a basis for their final report on the event. This report is available at the QUIE²T web site[2].

Apart from the scientific program, some extra-scientific events were organized at QIPC 2011. Specifically, under the auspices of QUIE²T WP1 a whole afternoon was used to stage another instance of an 'Industry Session', which has become already a regular feature for the QIPC conference series. After the successful Industry Sessions held at the previous QIPC meetings in Barcelona'07 and Rome'09, this event again offered a platform for exchanges between academic researchers and industry leaders.

The session in Zürich was held in the afternoon of Wednesday, Sep. 7, 2011. It was opened by QUIE²T work package leader Tommaso Calarco, who briefly explained the aim and the history of the activity. The session itself was hosted by QUIE²T work package leader Nicolas Gisin, who further explained the new format of having representatives from industry and academic research in the session.

[1] http://www.qipc2011.ethz.ch/

[2] http://qurope.eu/content/qipc-2011-conference-report/

Following that, there were presentations by **Dr. Bruno Michel**, from IBM Research, Zürich, who talked about '*Computing after scaling: New computation paradigms*', and **Dr. Grégoire Ribordy**, CEO of ID Quantique, who were celebrating their 10th anniversary this year. The title of his presentation was accordingly '*Commercializing QITechnology for 10 years*'.

On new and promising potential applications in quantum metrology there were presentations by two researchers, **Dr. Jürgen Appel** from the Niels Bohr Institute in Copenhagen, who talked about '*Mesoscopic atomic superposition states for metrology and QI*', and **Dr. Bruno Sanguinetti** from the Group of Applied Physics in Geneva with a presentation on '*Quantum cloning for absolute radiometry*'.

The event was well attended and sparked a number of interesting questions and lively discussions. At the end of the session, **IBM** announced they will organize a **workshop** in 2012 with invited scientists and EU representatives to assess the potential of quantum technologies. This workshop on 'New Computation Paradigms' was indeed held at the IBM Zürich Research laboratory in August 2012, but no external links are available for the event.

In addition to participating to the dedicated industry session, ID Quantique had a permanent stand at the conference, showcasing some of their commercial products, in particular QUANTIS (a true random-number generator) and CLAVIS^2 (a QKD research platform).

Plenary Program, QIPC 2011 @ HCI G3, ETH Hönggerberg, Zurich

	Starting Times	Monday, Sep. 5	Tuesday, Sep. 6	Wednesday, Sep. 7	Thursday, Sep. 8	Friday, Sep. 9
	9:00		**Young Investigator Award**	EU Funding Note		
	9:15	Opening Address	R. Hanson and S. Pironio			
	9:30	**Atomic Systems** (Tilman Esslinger)	**Superconducting Circuits** (Christoph Bruder)	**Photons** (Matthias Christandl)	**Mechanical Oscillators** (Tobias Kippenberg)	**Qu. Information Theory** (Gianni Blatter)
	9:30	Immanuel Bloch	Andrew Cleland	Eugene Polzik	Oskar Painter	Charles Bennett
	10:10	Aurelian Dantan	Andreas Dewes	Igor Dotsenko	Albert Schliesser	Beni Yoshida
	10:30	Stephen Hogan	Chris Wilson	Peter Shadbolt	Mika Sillanpää	Florian Fröwis
	10:50			Coffee Break, 30'		
	11:20	Rainer Blatt	Irfan Siddiqi	Konrad Lehnert	Florian Marquardt	Andreas Winter
Fri 2 - Sun 4 **QIPC School 2011** @ Berghaus Diavolezza	11:50	Peter Zoller	Yasunobu Nakamura	Paul Kwiat	John Teufel	Tobias Osborne
	12:20	Lunch, 1 h 20'	Lunch and odd numbered Posters, 2 h	Lunch and even numbered Posters, 2 h 13:20 -14:10 **EU Funding Session** @ E Floor Cafeteria	Lunch and odd numbered Posters, 1 h 20'	Lunch and even numbered Posters, 2 h
	13:40	**Quantum Communication** (Renato Renner)	**Parallel Sessions** **14:20** - 16:00, 5 x 20'	**Industry Session** **14:20** - 16:00 (Nicolas Gisin)	**Parallel Sessions** **13:40** - 15:20, 5 x 20'	**Parallel Sessions** **14:20** - 16:00, 5 x 20'
	13:40	Nicolas Gisin			E: Charges & Spins @ G3 F: Special Topics @ G7 G: Photons @ J3	
	14:20	Jürgen Eschner	A: Atomic Systems @ G3	Bruno Michel, 14:20		H: Mech. Oscillators @ G3
	14:40	Lars Lydersen	B: Qu. Communication @ G7	Grégoire Ribordy, 15:00		I: Atomic Systems @ G7
	15:00	Matthias Christandl	C: Supercond. Circuits @ J3	Jürgen Appel, 15:20		J: Qu. Inf. Theory @ J3
	15:30	Jens Eisert	D: Charges & Spins @ J7	Bruno Sanguinetti, 15:40	Coffee Break, 30'	
	16:00		Coffee Break, 30'		**Atomic Systems** **15:50** - 18:10 (Jonathan Home)	Coffee Break, 30'
	16:30	**Charges & Spins** (Daniel Loss)	**Special Topics** (Peter Zoller)	**Charges & Spins** (Thomas Ihn)	Chris Monroe, 15:50	**Topical Sessions**
	16:30	Amir Yacoby	Ignacio Cirac	Misha Lukin	Kenton Brown, 16:30	Geometric and Topological Phases @ G7
Sun 4, 17 - 20:00 **Welcome Reception** @ Faculty Lounge, ETH Main Building	17:10	Sergey Frolov	Philip Walther	Matthieu Delbecq	Stephan Ritter, 16:50	
	17:30	Peter Leek	Philippe Corboz	Ronald Hanson	Philipp Treutlein, 17:10	
	17:50	Lieven Vandersypen	Christophe Salomon	David Awschalom	Dieter Meschede, 17:40	Q-ESSENCE
	18:20	Charles Marcus	Fabian Hassler	Andrea Morello	Bus Transport to Kunsthaus at **18:30** & **18:45**	Business Meeting @ J7
			20:00 - 23:00 **Open Mike Discussion** @ Vis Dome, ETH Main Building		19:00 - 24:00 **Conference Event and Dinner** @ Kunsthaus	
	Colors:	Invited Introductory, 40'	Contributed Hot Topic, 20'	Invited Topical, 30'	Contibuted, 5 x 20'	Other Events and Sessions

Commercializing Quantum Information Technology for 10 Years

« Surviving with Quantum InformationTechnology for 10 Years »

QIPC 2011 Industry Session - Zurich

Grégoire Ribordy
www.idquantique.com

Outline

Standard Model of New Venture Funding

+ Fools

January 2012

4th Winter School on Practical Quantum Cryptography

Dates: Monday January 23 to Thursday January 26, 2012

Location: Les Diablerets, Switzerland

More: **www.idquantique.com** **or** **info@idquantique.com**

Scholarships Available: Contact us by email

Pictures from the Winter School 2nd Edition

Key note speakers include:
- Nicolas Gisin
- Renato Renner
- Vadim Makarov

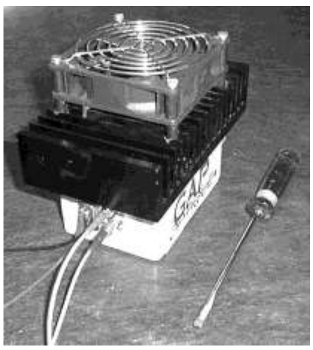
Winter School 1 – 3:
- over 45 participants
- from industry and academia
- from 5 continents

Year 2001

University of Geneva, 1998

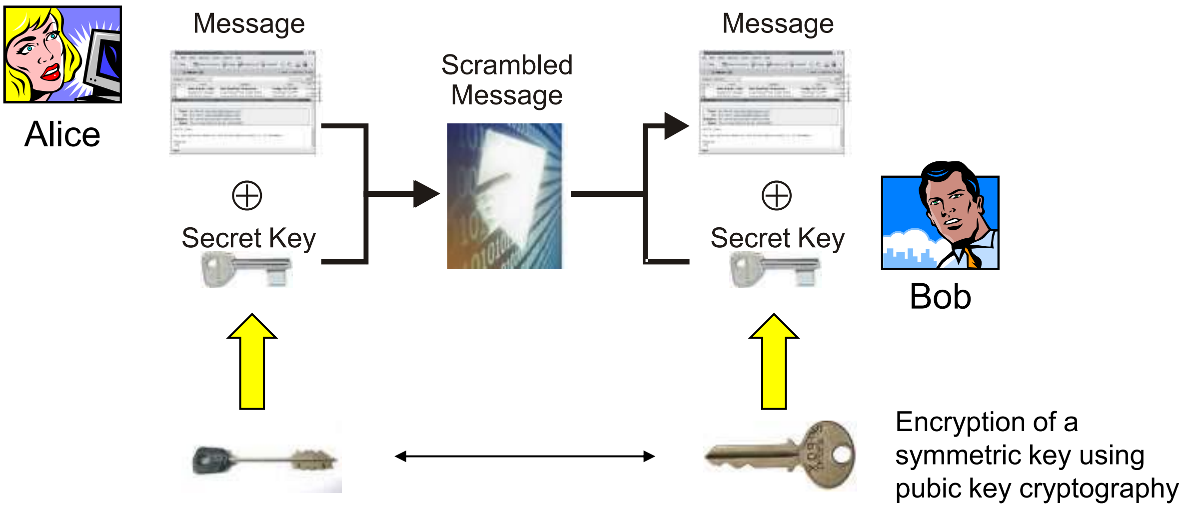
ID Quantique, 2001

Single-Photon Detector
with LN2 Cooling



Single-Photon Detector
with Thermo-electric cooling

Cryptography



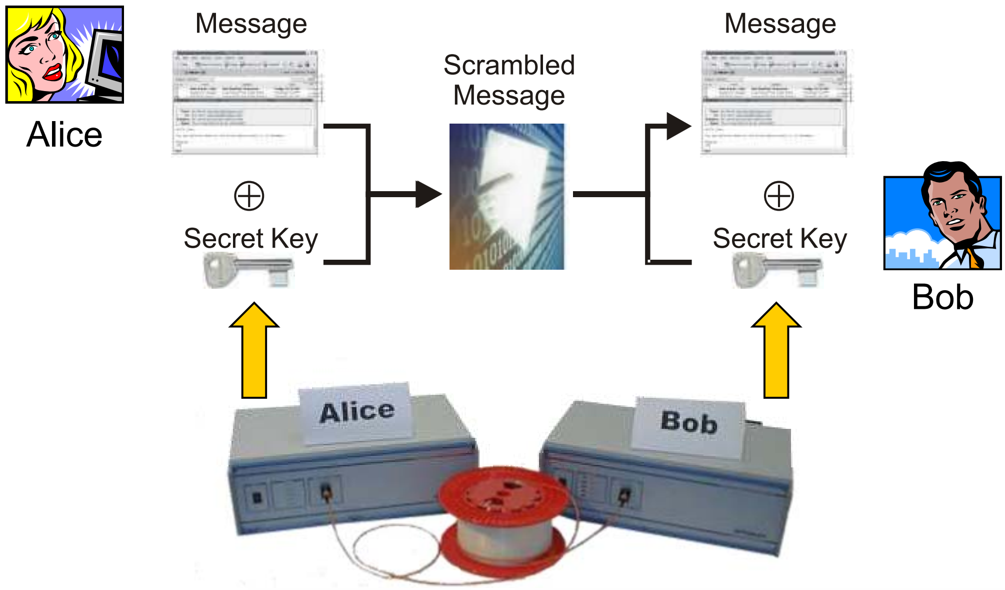
The Limits of Public Key Cryptography

- The security of the most popular public key algorithms cannot be formally proven.
  - Example: The security of RSA is based on the difficulty to factorize large numbers

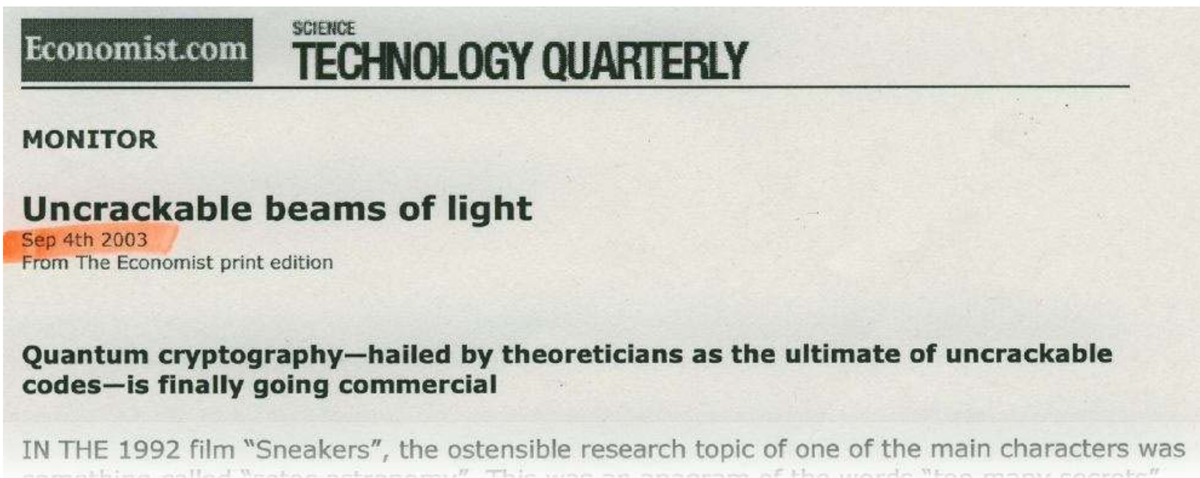
    65497 x 92951 = 6088011647

  - But…
    - The difficulty of factoring is not formally proven
    - Factorization is « easy » with a quantum computer

Key Distribution



Absolute Security



Economist.com

SCIENCE
TECHNOLOGY QUARTERLY

MONITOR

Uncrackable beams of light

Sep 4th 2003
From The Economist print edition

Quantum cryptography—hailed by theoreticians as the ultimate of uncrackable codes—is finally going commercial

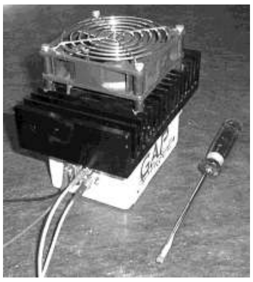
IN THE 1992 film "Sneakers", the ostensible research topic of one of the main characters was

2001 - 2003

From 1 to 3 Employees

Founders Capital → Family & Friends → Angel & Early VC → Venture Capital → Expansion Capital

Revenues



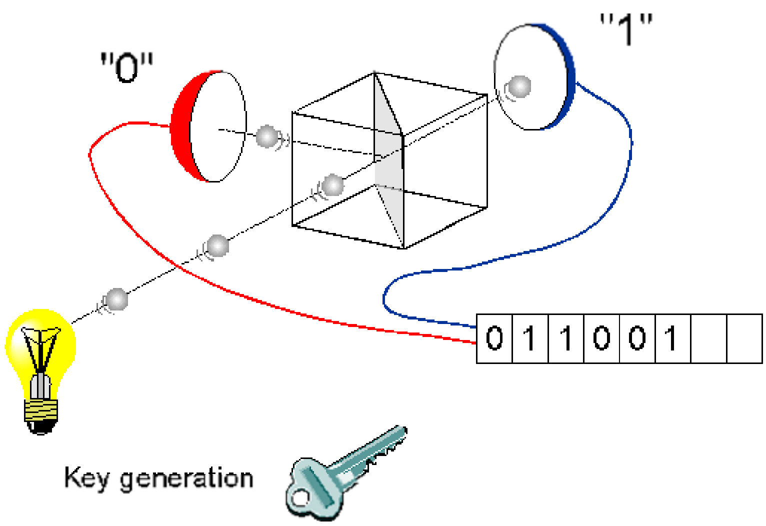
Quantum RNG

NEW

Windows

Linux

Solaris



2001 - 2003

From 1 to 3 Employees

Founders Capital
Family & Friends
Angel & Early VC
Venture Capital
Expansion Capital

Revenues

EU R&D Funding

Awards

Lesson: Consider Alternative Funding Models

2004

From 3 to 12 Employees

Founders Capital
Family & Friends
Angel & Early VC
Venture Capital
Expansion Capital

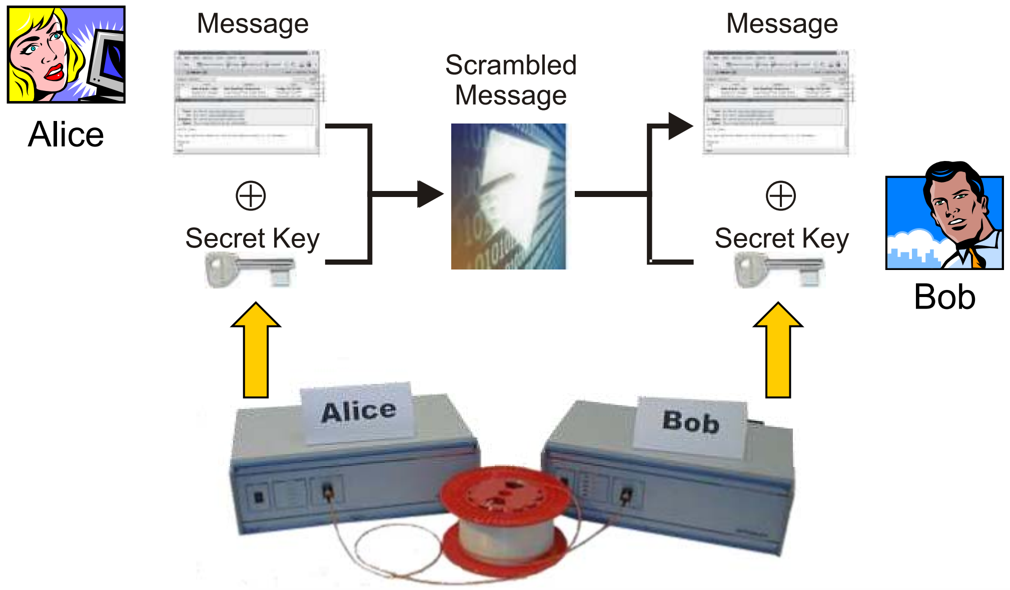
Revenues

EU R&D Funding

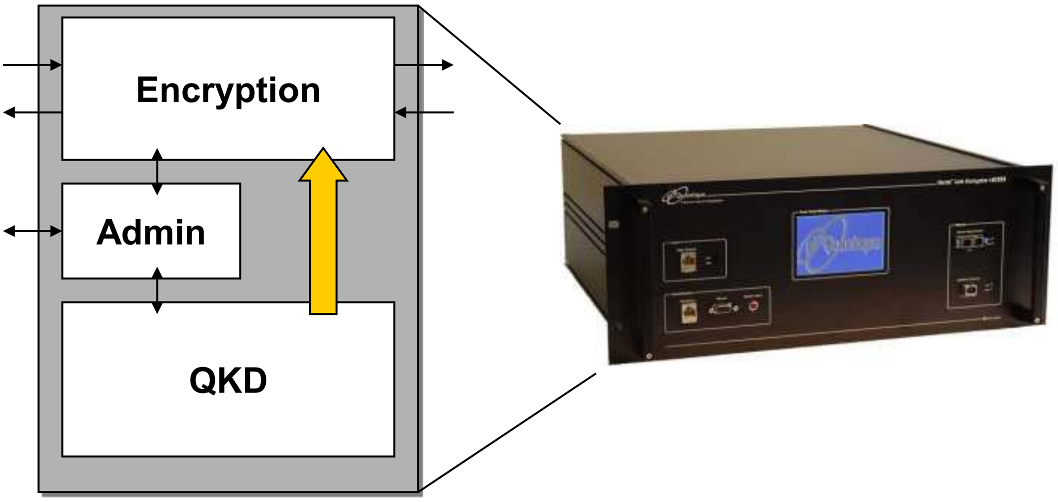
Awards

1 M EUR
- Danish investor
- Living in London
- Operating out of Luxemburg

Key Distribution



QKD Solution Development 1/2



QKD Solution 2/2

=

Encryption

+

Quantum Key Distribution

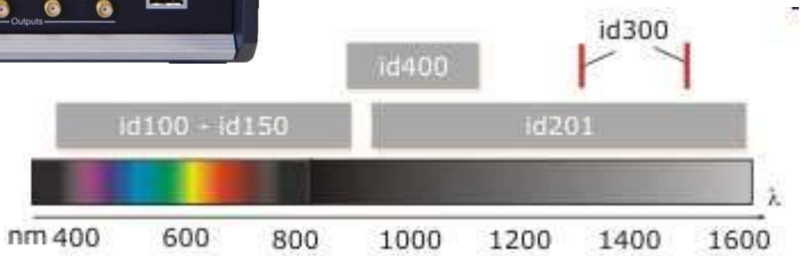
Lesson: Question the View of Incumbent Players

2008 - …

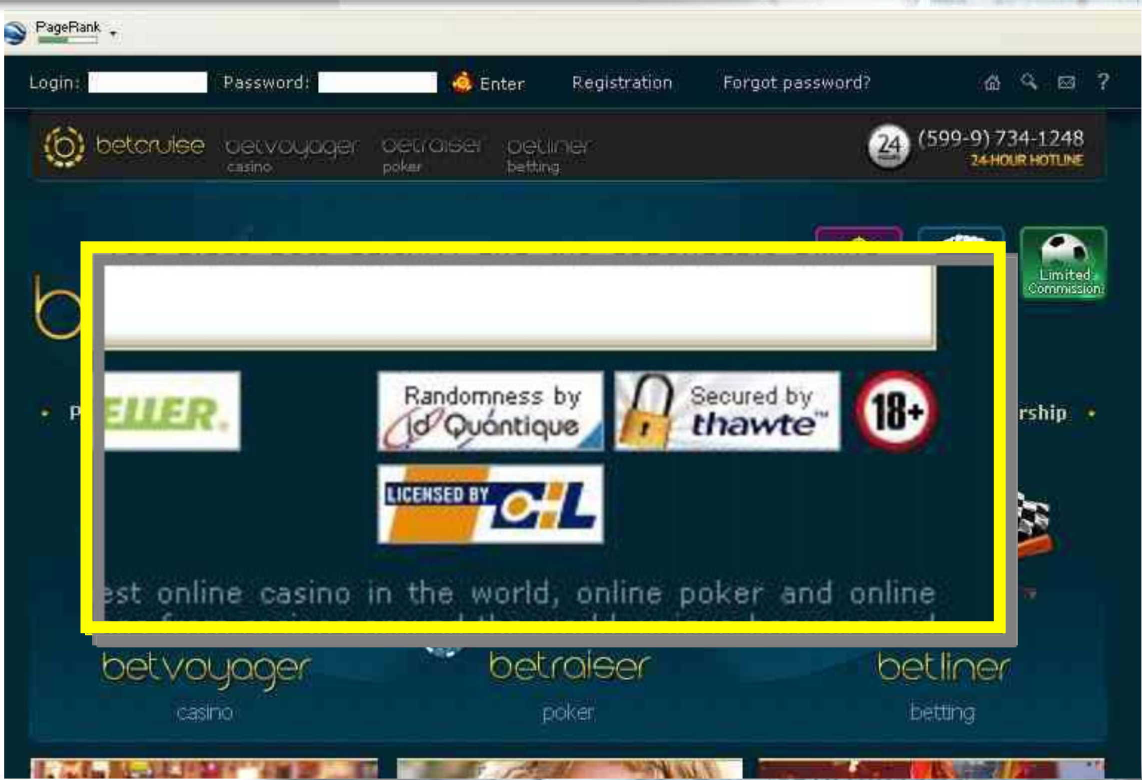
From 12 to 20 Employees
3 Business Units
- Scientific Instrumentation
- Random Number Generator
- Network Encryption

Scientific Instrumentation

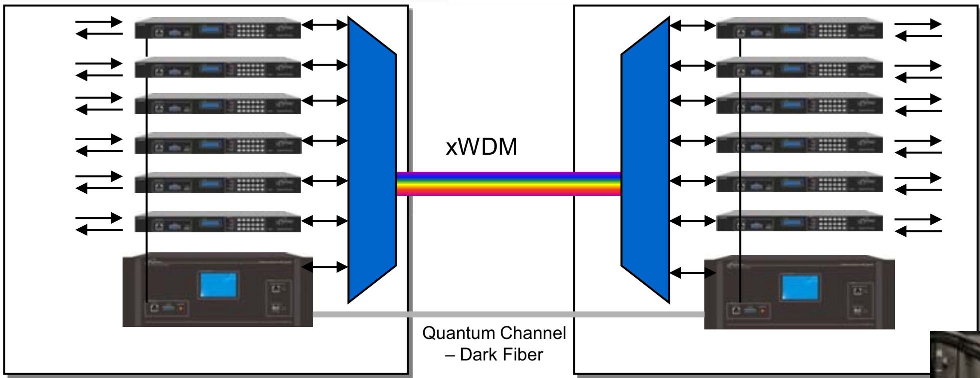
June 2011: id210
InGaAs APD SPD
Free Running Operation
Gating up to 100MHz



Random Number Generator



Siemens IT Services and Solutions B.V.



Data Center
(The Hague)

Data Center
(Zoetermeer)

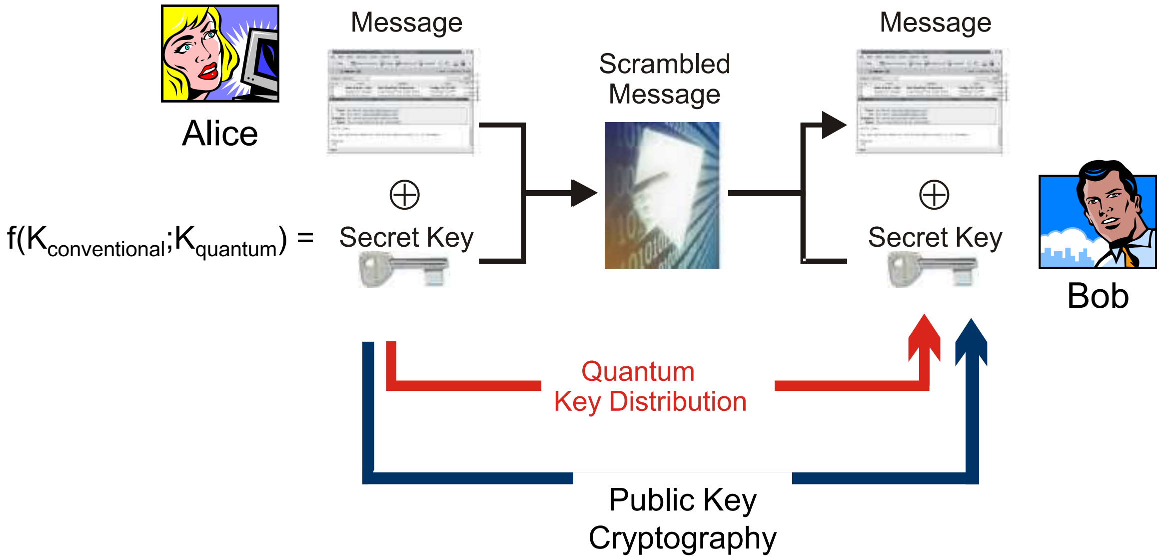
SIEMENS
Siemens IT Solutions and Services

Q4 2010

Acceptance of QKD Technology

- Certification (or lack of…)
- Reliability and References
- Costs (Equipment and Total Cost of Ownership)
- Practical Security

Network Encryption



From **Absolute Security** to **Forward Secrecy**

Lesson: QKD will not replace Conventional Technology but complement it

Acceptance of QKD Technology

- ❑ Certification (or lack of…)
- ❑ Reliability and References
- ❑ Costs (Equipment and Total Cost of Ownership)
- ❑ Practical Security

SwissQuantum Testbed

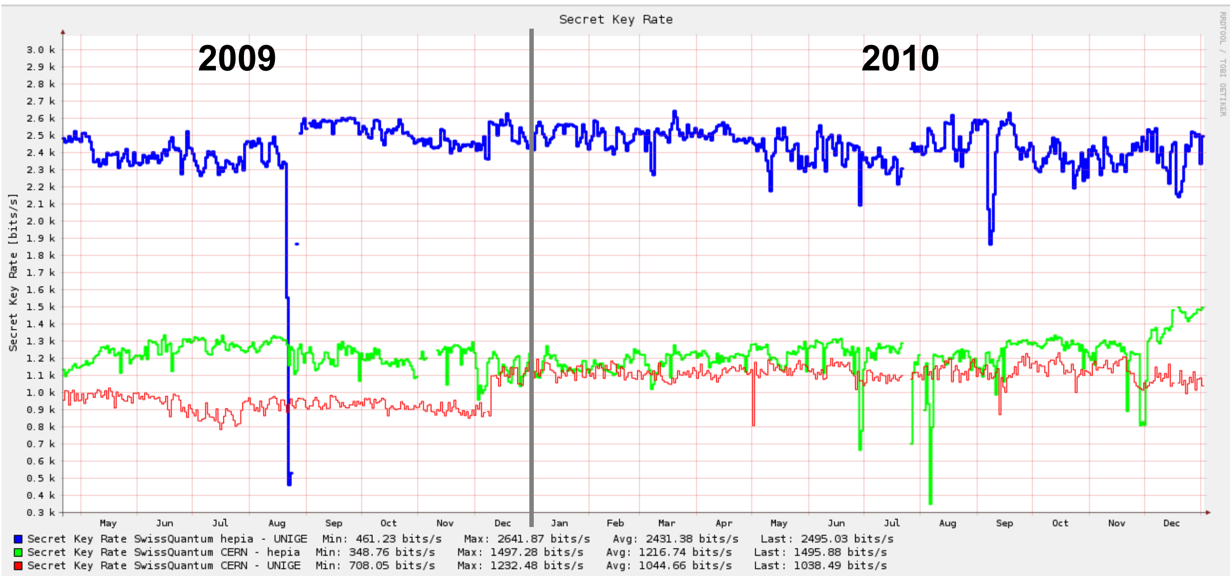
UNIVERSITÉ DE GENÈVE

IDQ FROM VISION TO TECHNOLOGY

Hes·so Haute Ecole Spécialisée de Suisse occidentale

CERN

SwissQuantum Peformance



www.swissquantum.com

Cumulative operation time of 45’000+ hours

Acceptance of QKD Technology

- Certification (or lack of…)
- Reliability and References
- Costs (Equipment and Total Cost of Ownership)
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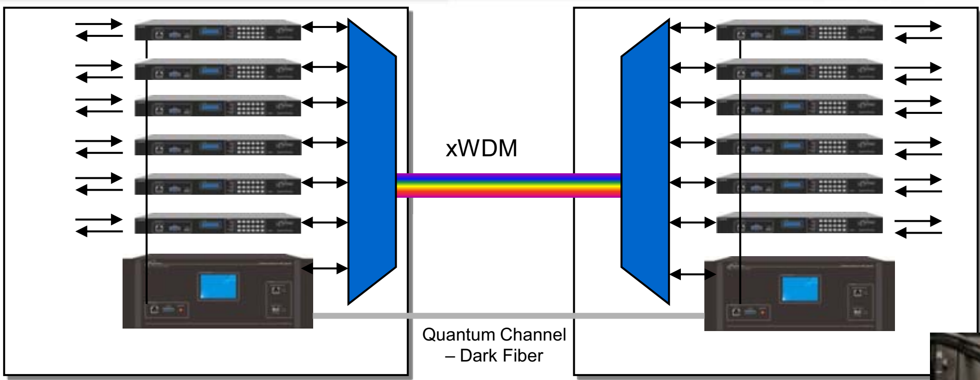
Siemens IT Services and Solutions B.V.



Data Center
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SIEMENS

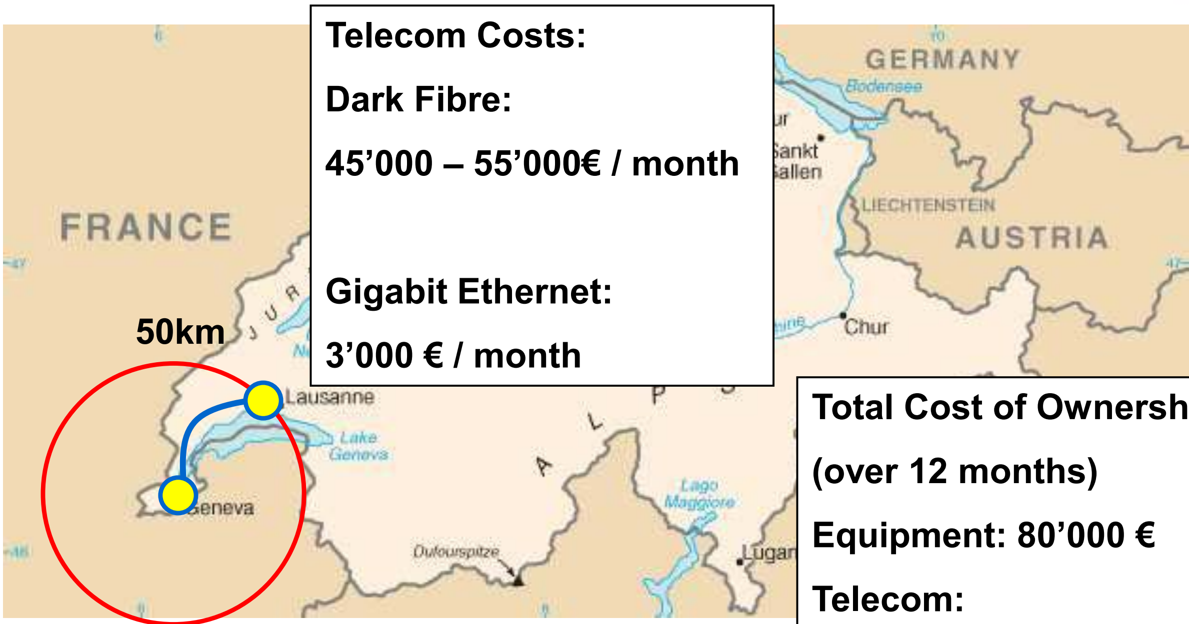
Siemens IT Solutions and Services

Q4 2010

Difficulties of Deployment

Dark Fiber is ok (costs, availability) over 10km, but less over 50km

Case Study: Swiss Bank



Telecom Costs:

Dark Fibre:

45'000 – 55'000€ / month

Gigabit Ethernet:

3'000 € / month

Total Cost of Ownership:

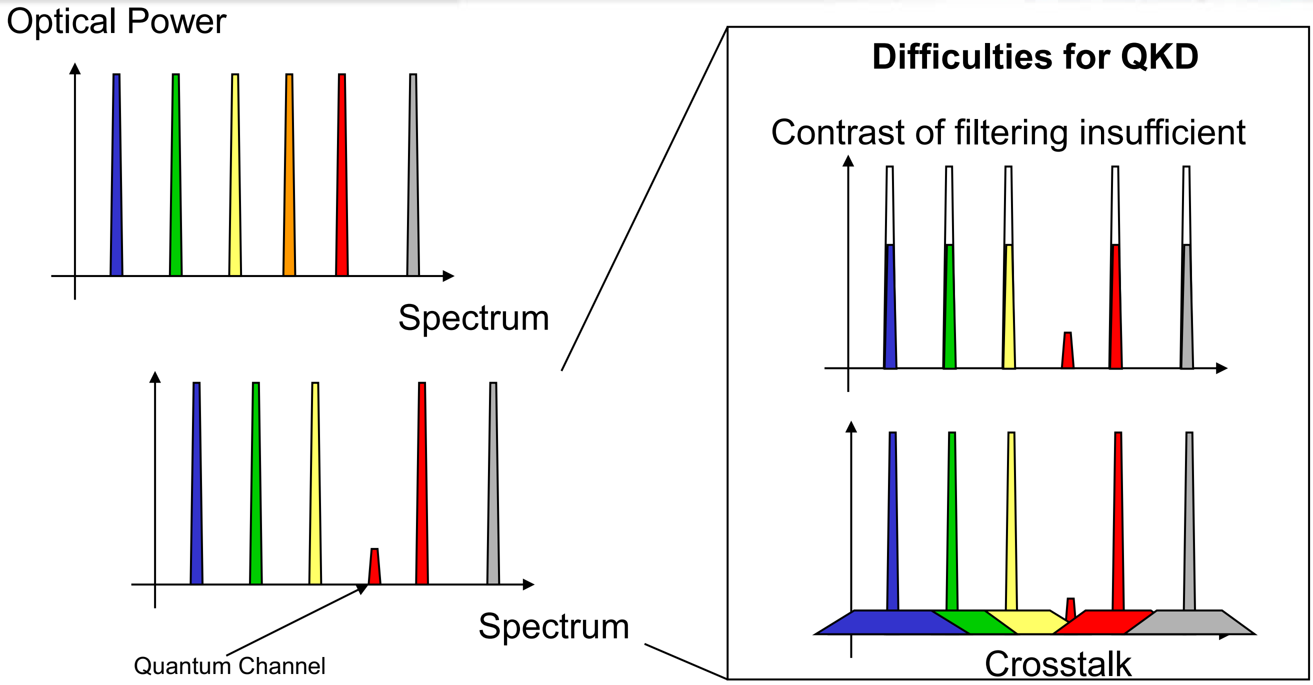
(over 12 months)

Equipment: 80'000 €

Telecom:

540'000 – 660'000 €

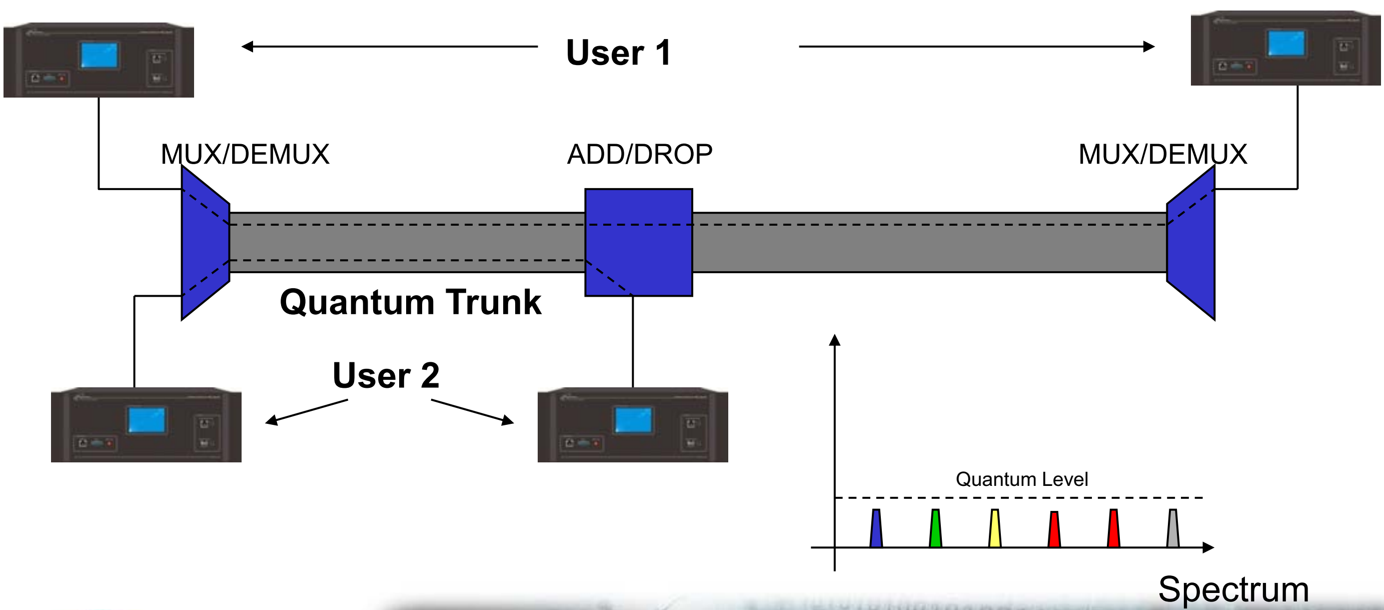
Wavelength Division Multiplexing



QKD over WDM can work over 10-20 km but not 50-100km

Solutions

- ❑ Invent new business models: WDM for Quantum Channel only



Acceptance of QKD Technology

- Certification (or lack of…)
- Reliability and References
- Costs (Equipment and Total Cost of Ownership)
- Practical Security

Quantum Hacking

QKD cannot be brokem; A QKD implementation can!

Vadim Makarov, Norwegian University of Science and Technology

Thank you for your attention…

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Support

QuReP
Quantum Repeaters for Long Distance Fibre-Based Quantum Communication

QUESSENCE

Quantum Cloning for Absolute Radiometry

Bruno Sanguinetti, Thiago Guerreiro, Enrico Pomarico, Rob Thew, Hugo Zbinden and Nicolas Gisin
GAP Optique

Silke Peters and Stefan Kück
PTB

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique appliquée

Physikalisch-Technische Bundesanstalt

Radiometry and Quantum Mechanics

A Long Term Relationship

vendredi 28 septembre 12

1892: Lummer creates the substitution radiometer

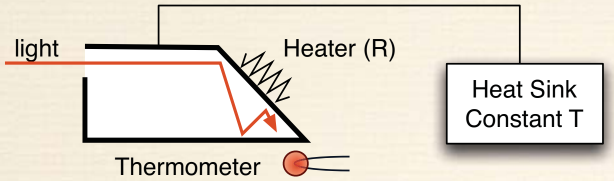

Fig. 5.

1. Lummer, O. & Kurlbaum, F. Bolometrische Untersuchungen. Ann. Phys. 282, 204–224 (1892). (6 citations)

isi: 1141 articles on heat transfer in cattle, 30 in 2011!

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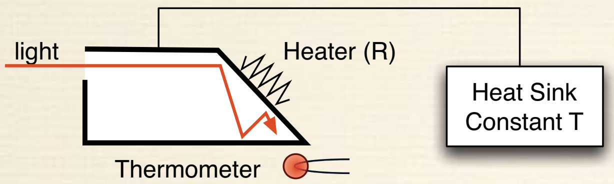

- Works at 'high' powers (mW)
- Current needs to be calibrated
- Complex experiment
- Still the reference today

Fig. 5.

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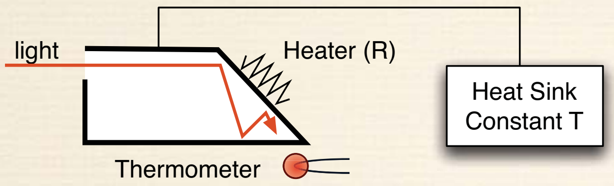

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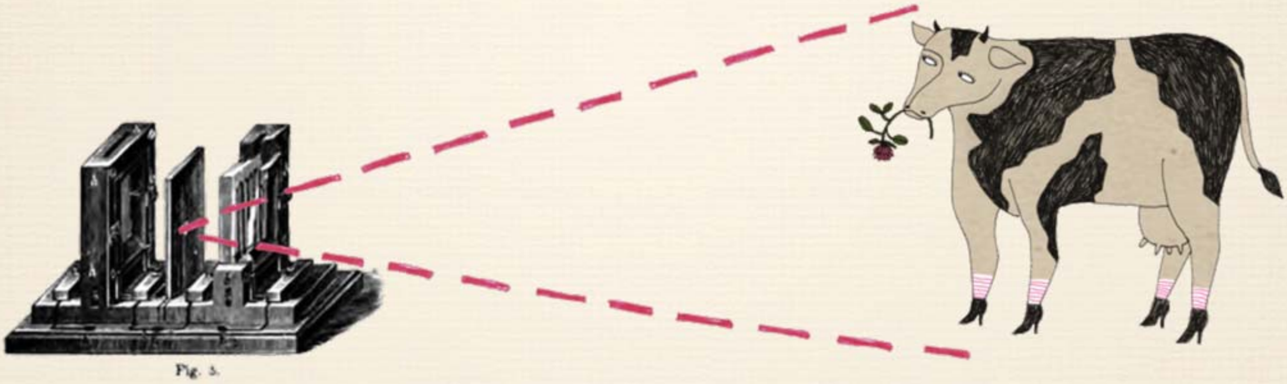


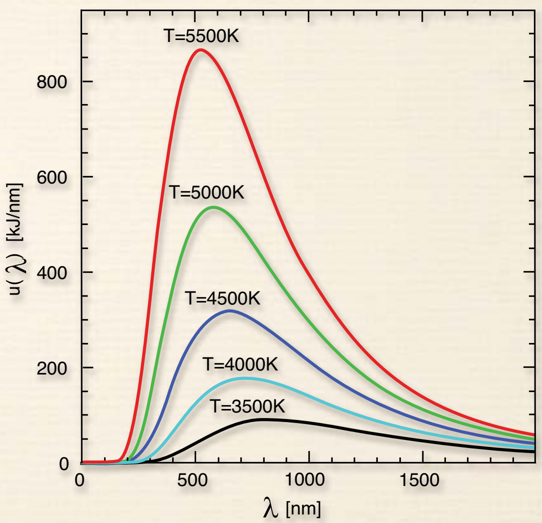
1. Lummer, O. & Kurlbaum, F. Bolometrische Untersuchungen. Ann. Phys. 282, 204–224 (1892). (6 citations)

isi: 1141 articles on heat transfer in cattle, 30 in 2011!

1900: Max Planck explains the blackbody spectrum: Quantum Mechanics is born.

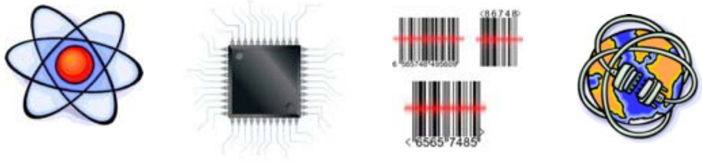
$$E = h\nu$$

Max Planck



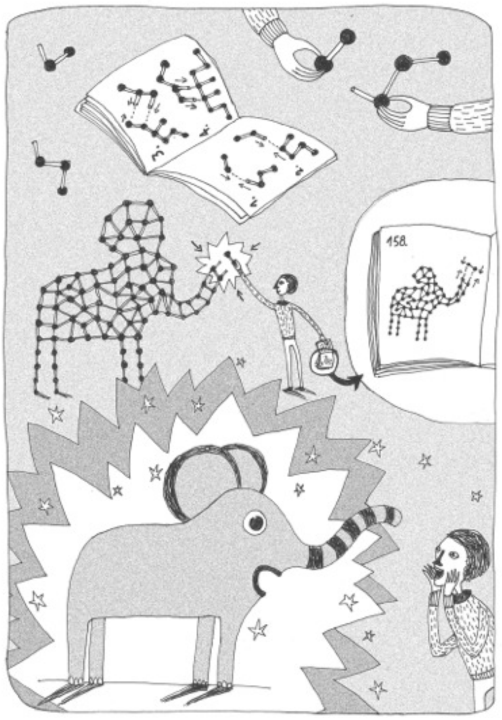
1. Planck, M. Ueber eine Verbesserung der Wien'schen Spectralgleichung; von M. Planck. Verhandlungen der Deutschen physikalischen Gesellschaft 2, 687 (1901).

One century goes by ...

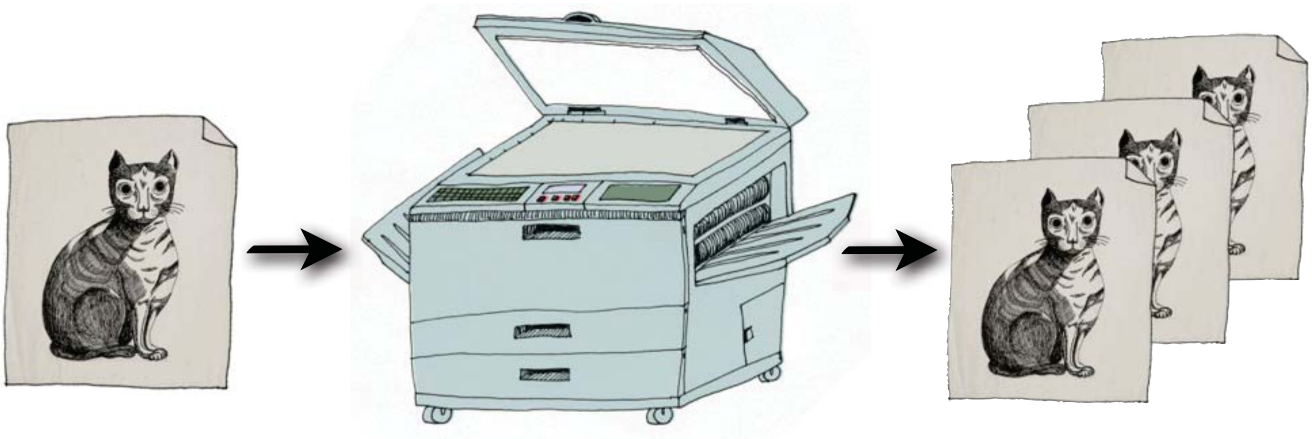


One century goes by ...

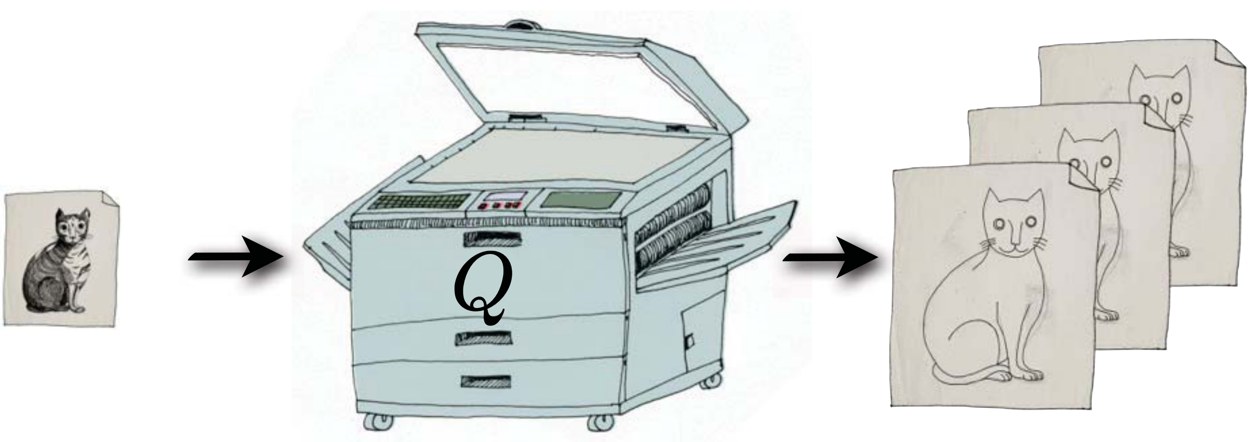
... there still are some open questions, such as what is the quantum to classical transition



Copying information is different in the Quantum and Macroscopic worlds



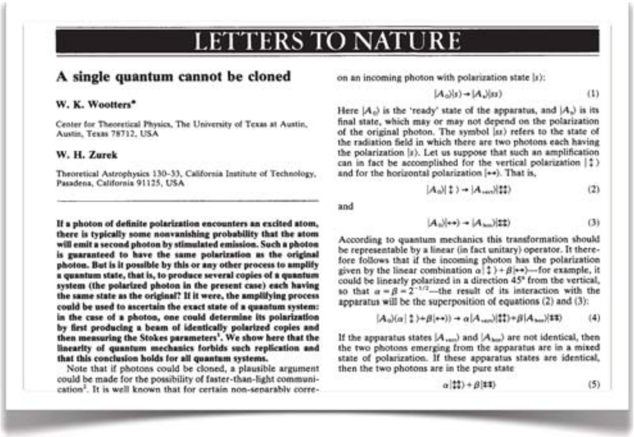
Copying information is different in the Quantum and Macroscopic worlds



Quantum cloning: copying, but not perfectly

vendredi 28 septembre 12

“no(perfect)-cloning” is fundamental



LETTERS TO NATURE

A single quantum cannot be cloned

W. K. Wootters*

Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712, USA

W. H. Zurek

Theoretical Astrophysics 130-33, California Institute of Technology, Pasadena, California 91125, USA

If a photon of definite polarization encounters an excited atom, there is typically some nonvanishing probability that the atom will emit a second photon by stimulated emission. Such a photon is guaranteed to have the same polarization as the original photon. But is it possible by this or any other process to amplify a quantum state, that is, to produce several copies of a quantum system (the polarized photon in the present case) each having the same state as the original? If it were, the amplifying process could be used to ascertain the exact state of a quantum system: in the case of a photon, one could determine its polarization by first producing a beam of identically polarized copies and then measuring the Stokes parameters[1]. We show here that the linearity of quantum mechanics forbids such replication and that this conclusion holds for all quantum systems.

Note that if photons could be cloned, a plausible argument could be made for the possibility of faster-than-light communication[2]. It is well known that for certain non-separably corre-

on an incoming photon with polarization state $|s\rangle$:

$$|A_0\rangle|s\rangle \rightarrow |A_s\rangle|ss\rangle \quad (1)$$

Here $|A_0\rangle$ is the 'ready' state of the apparatus, and $|A_s\rangle$ is its final state, which may or may not depend on the polarization of the original photon. The symbol $|ss\rangle$ refers to the state of the radiation field in which there are two photons each having the polarization $|s\rangle$. Let us suppose that such an amplification can in fact be accomplished for the vertical polarization $|\updownarrow\rangle$ and for the horizontal polarization $|\leftrightarrow\rangle$. That is,

$$|A_0\rangle|\updownarrow\rangle \rightarrow |A_{vert}\rangle|\updownarrow\updownarrow\rangle \quad (2)$$

and

$$|A_0\rangle|\leftrightarrow\rangle \rightarrow |A_{hor}\rangle|\leftrightarrow\leftrightarrow\rangle \quad (3)$$

According to quantum mechanics this transformation should be representable by a linear (in fact unitary) operator. It therefore follows that if the incoming photon has the polarization given by the linear combination $\alpha|\updownarrow\rangle + \beta|\leftrightarrow\rangle$—for example, it could be linearly polarized in a direction 45° from the vertical, so that $\alpha = \beta = 2^{-1/2}$—the result of its interaction with the apparatus will be the superposition of equations (2) and (3):

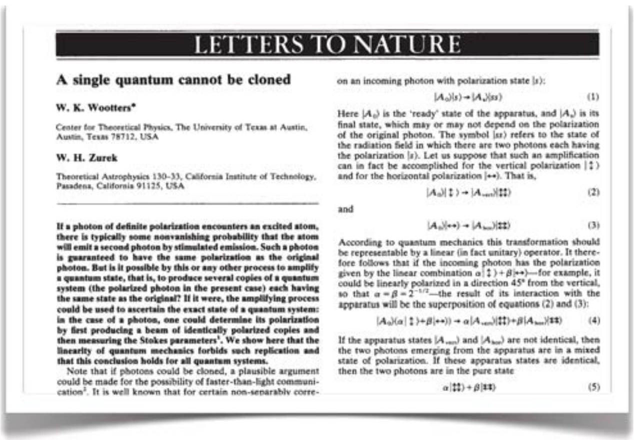
$$|A_0\rangle(\alpha|\updownarrow\rangle + \beta|\leftrightarrow\rangle) \rightarrow \alpha|A_{vert}\rangle|\updownarrow\updownarrow\rangle + \beta|A_{hor}\rangle|\leftrightarrow\leftrightarrow\rangle \quad (4)$$

If the apparatus states $|A_{vert}\rangle$ and $|A_{hor}\rangle$ are not identical, then the two photons emerging from the apparatus are in a mixed state of polarization. If these apparatus states are identical, then the two photons are in the pure state

$$\alpha|\updownarrow\updownarrow\rangle + \beta|\leftrightarrow\leftrightarrow\rangle \quad (5)$$

“no(perfect)-cloning” is fundamental

- Without it:
  - No uncertainty principle



LETTERS TO NATURE

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$$|A_0\rangle|\updownarrow\rangle \rightarrow |A_{vert}\rangle|\updownarrow\updownarrow\rangle \quad (2)$$

and

$$|A_0\rangle|\leftrightarrow\rangle \rightarrow |A_{hor}\rangle|\leftrightarrow\leftrightarrow\rangle \quad (3)$$

According to quantum mechanics this transformation should be representable by a linear (in fact unitary) operator. It therefore follows that if the incoming photon has the polarization given by the linear combination $\alpha|\updownarrow\rangle + \beta|\leftrightarrow\rangle$—for example, it could be linearly polarized in a direction 45° from the vertical, so that $\alpha = \beta = 2^{-1/2}$—the result of its interaction with the apparatus will be the superposition of equations (2) and (3):

$$|A_0\rangle(\alpha|\updownarrow\rangle + \beta|\leftrightarrow\rangle) \rightarrow \alpha|A_{vert}\rangle|\updownarrow\updownarrow\rangle + \beta|A_{hor}\rangle|\leftrightarrow\leftrightarrow\rangle \quad (4)$$

If the apparatus states $|A_{vert}\rangle$ and $|A_{hor}\rangle$ are not identical, then the two photons emerging from the apparatus are in a mixed state of polarization. If these apparatus states are identical, then the two photons are in the pure state

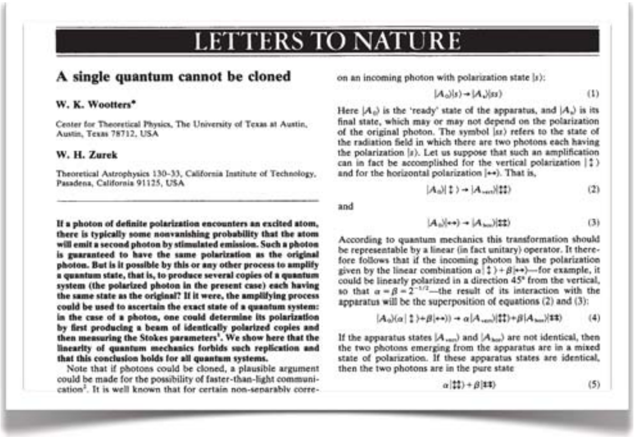
$$\alpha|\updownarrow\updownarrow\rangle + \beta|\leftrightarrow\leftrightarrow\rangle \quad (5)$$

Werner Heisenberg

vendredi 28 septembre 12

“no(perfect)-cloning” is fundamental

- Without it:
  - No uncertainty principle
  - Faster than light communication



LETTERS TO NATURE

A single quantum cannot be cloned

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W. H. Zurek

Theoretical Astrophysics 130-33, California Institute of Technology, Pasadena, California 91125, USA

If a photon of definite polarization encounters an excited atom, there is typically some nonvanishing probability that the atom will emit a second photon by stimulated emission. Such a photon is guaranteed to have the same polarization as the original photon. But is it possible by this or any other process to amplify a quantum state, that is, to produce several copies of a quantum system (the polarized photon in the present case) each having the same state as the original? If it were, the amplifying process could be used to ascertain the exact state of a quantum system: in the case of a photon, one could determine its polarization by first producing a beam of identically polarized copies and then measuring the Stokes parameters[1]. We show here that the linearity of quantum mechanics forbids such replication and that this conclusion holds for all quantum systems.

Note that if photons could be cloned, a plausible argument could be made for the possibility of faster-than-light communication[2]. It is well known that for certain non-separably corre-

on an incoming photon with polarization state $|s\rangle$:

$$|A_0\rangle|s\rangle \rightarrow |A_s\rangle|ss\rangle \quad (1)$$

Here $|A_0\rangle$ is the 'ready' state of the apparatus, and $|A_s\rangle$ is its final state, which may or may not depend on the polarization of the original photon. The symbol $|ss\rangle$ refers to the state of the radiation field in which there are two photons each having the polarization $|s\rangle$. Let us suppose that such an amplification can in fact be accomplished for the vertical polarization $|\updownarrow\rangle$ and for the horizontal polarization $|\leftrightarrow\rangle$. That is,

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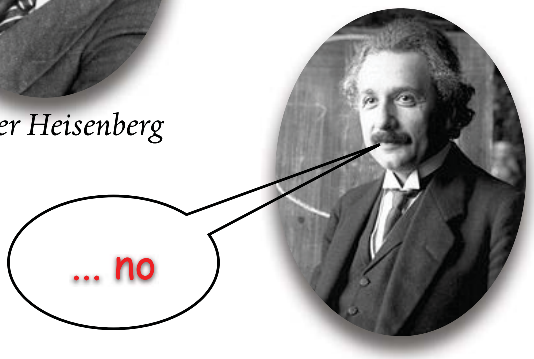
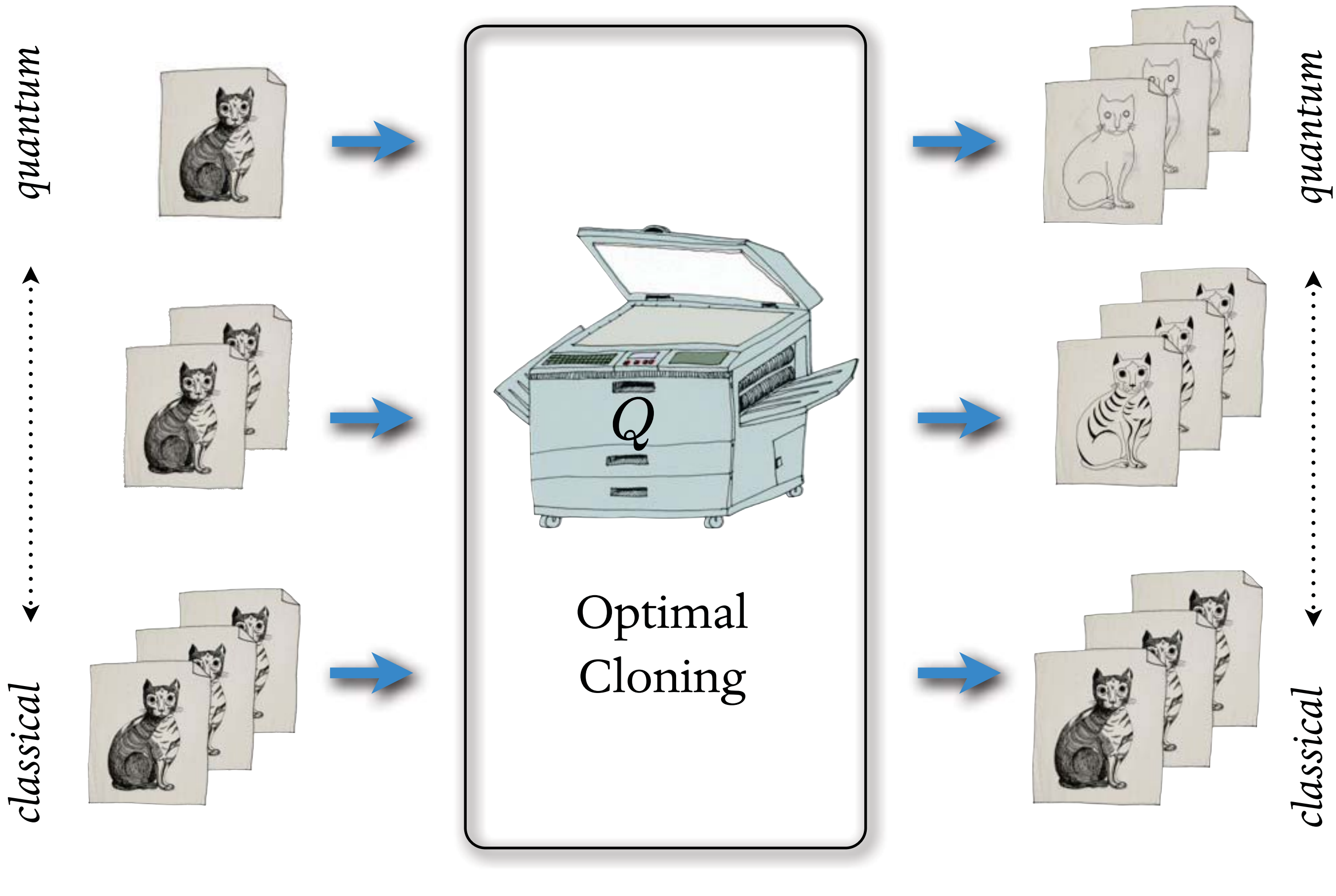
Werner Heisenberg



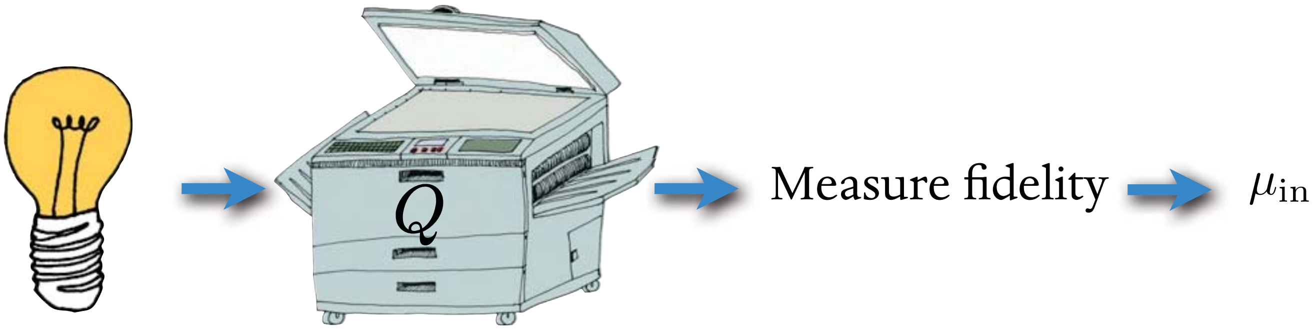
Albert Einstein

vendredi 28 septembre 12

Having more input copies improves fidelity



vendredi 28 septembre 12

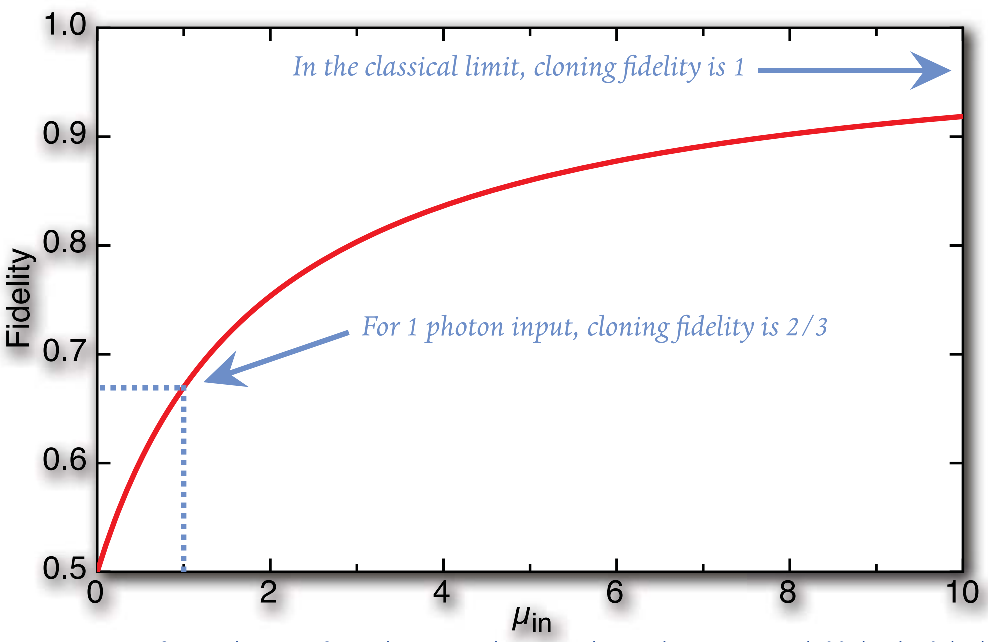


Quantitatively:

Cloning from N to M photons, the Fidelity $\mathcal{F}$ is: $\mathcal{F}_{N \to M} = \dfrac{NM + N + M}{NM + 2M}$

This can be written in terms of the input spectral randiance $\mu_{\text{in}}$and the gain G:

$$\mu_{\text{in}} = \frac{2\,\mathcal{F}\,G - G - 2\mathcal{F} + 1}{G - \mathcal{F}\,G} \simeq \frac{2\mathcal{F} - 1}{1 - \mathcal{F}}$$



Gisin and Massar. Optimal quantum cloning machines. Phys. Rev. Lett. (1997) vol. 79 (11) pp. 2153-2156

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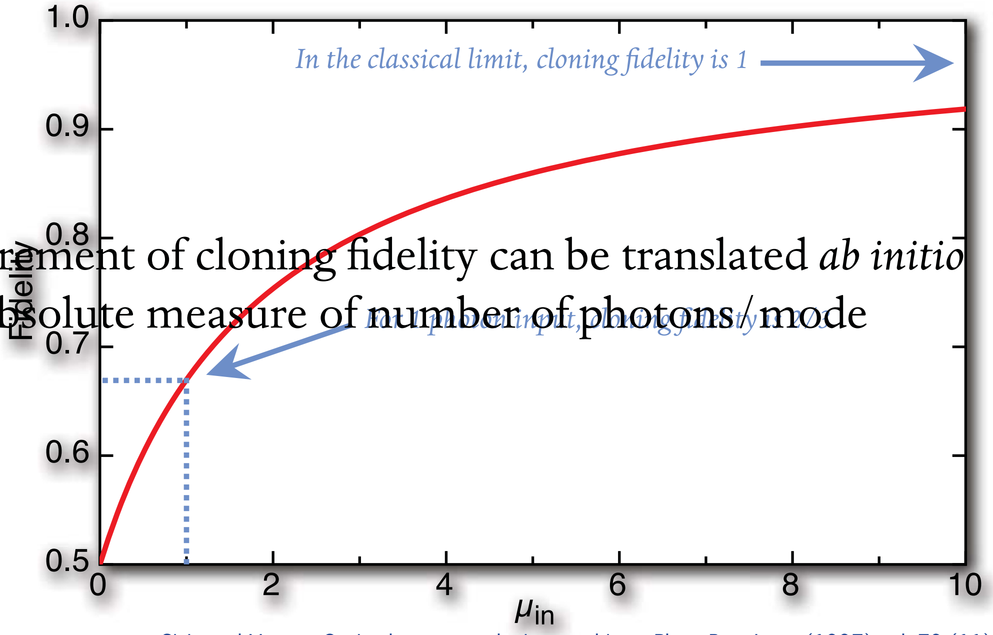
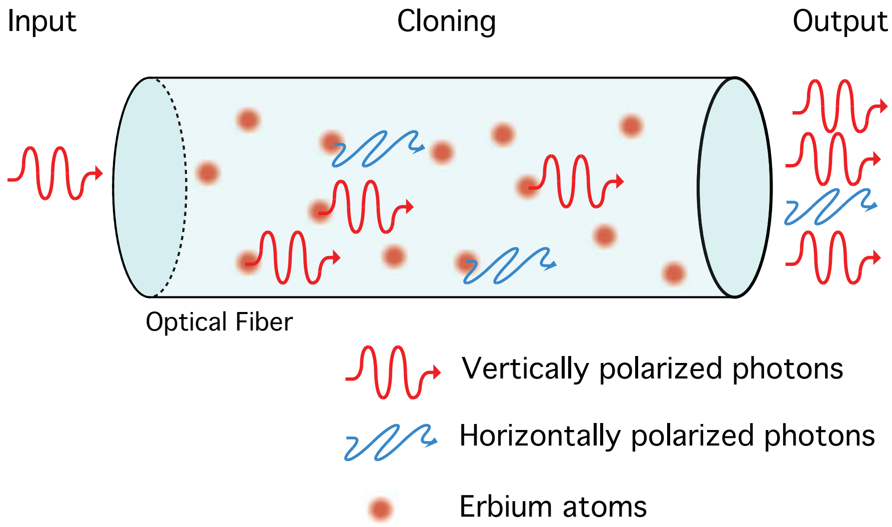


A measurement of cloning fidelity can be translated *ab initio* into an absolute measure of number of photons/mode

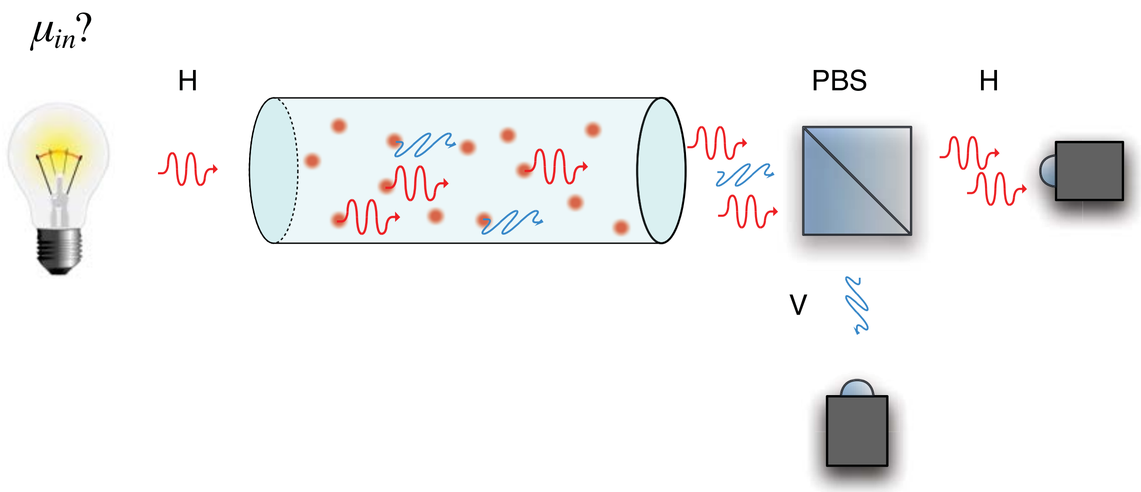
Gisin and Massar. Optimal quantum cloning machines. Phys. Rev. Lett. (1997) vol. 79 (11) pp. 2153-2156

Experiment

Cloning can be provided by stimulated emission in an Erbium doped fibre

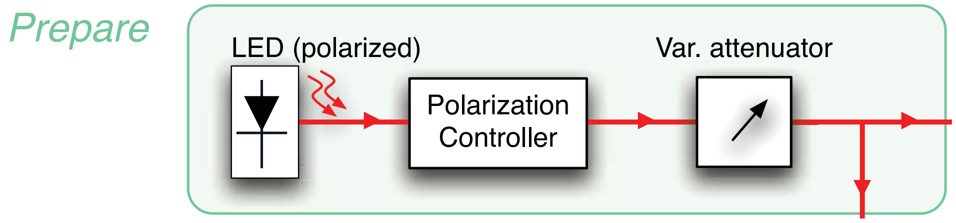


Conceptual setup of the radiometer

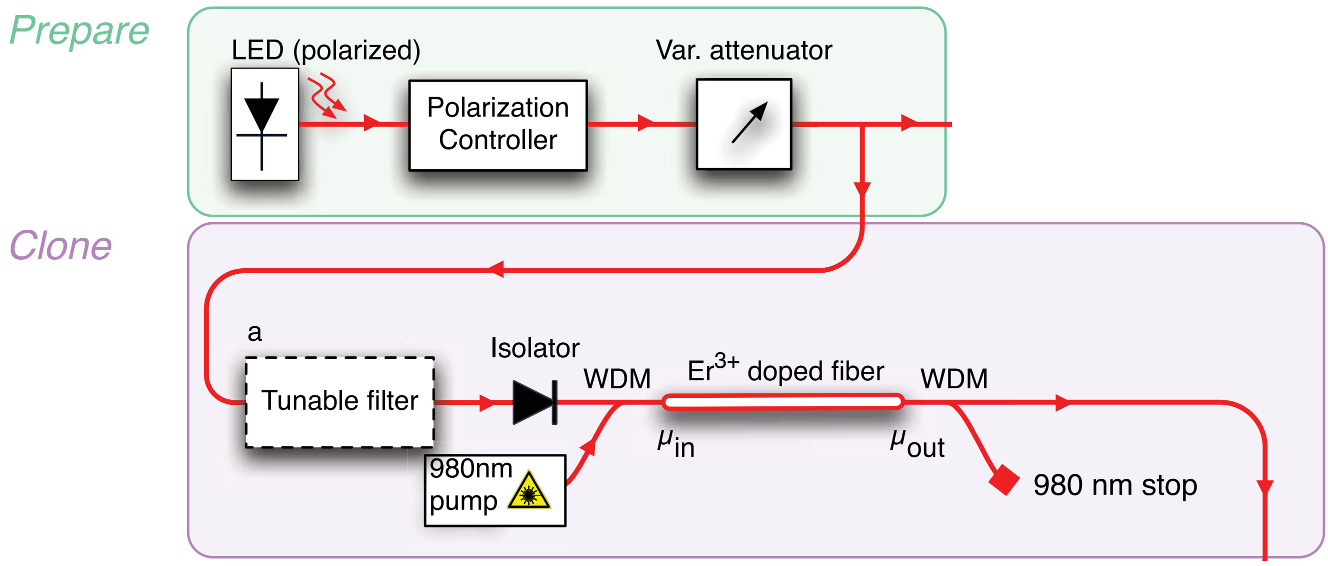


$$\mathcal{F} = \frac{P_{\parallel}}{P_{\parallel} + P_{\perp}}$$

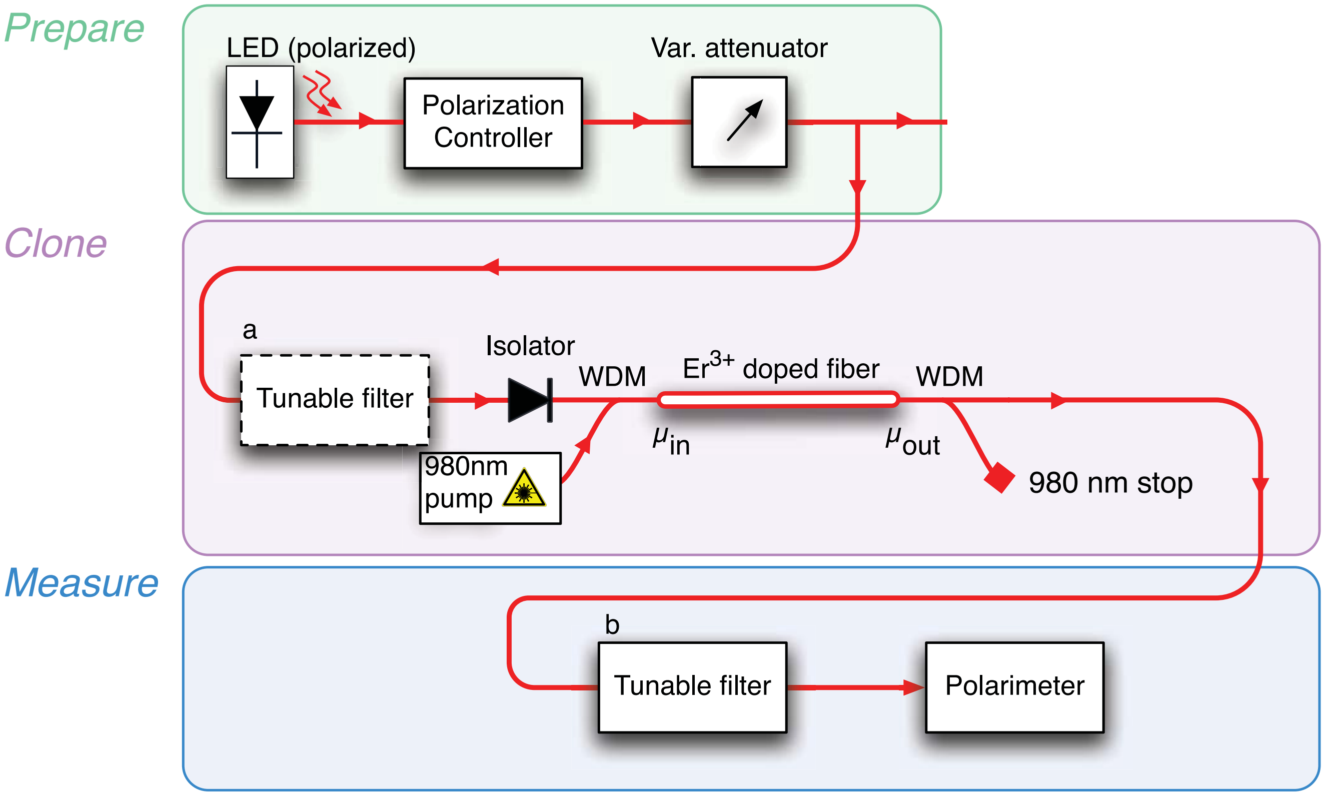
Real setup



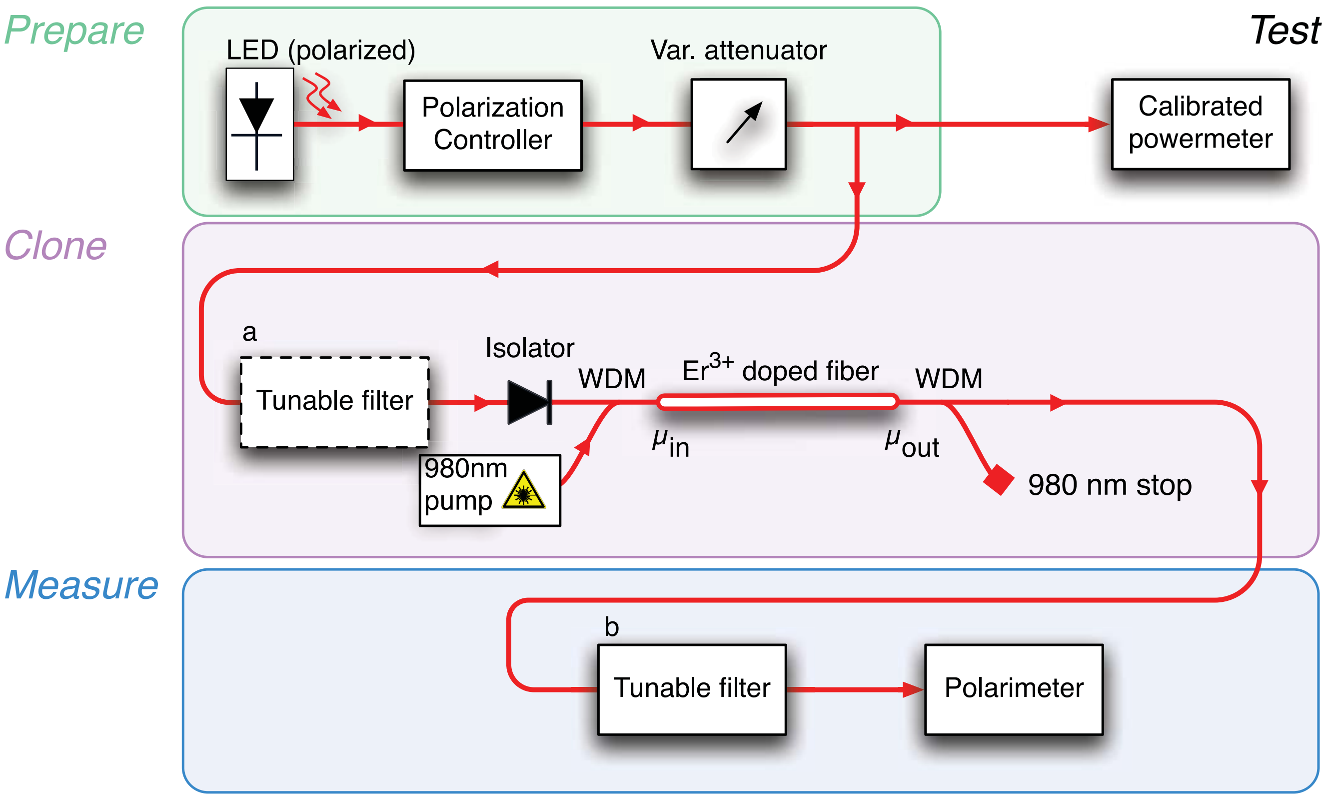
Real setup

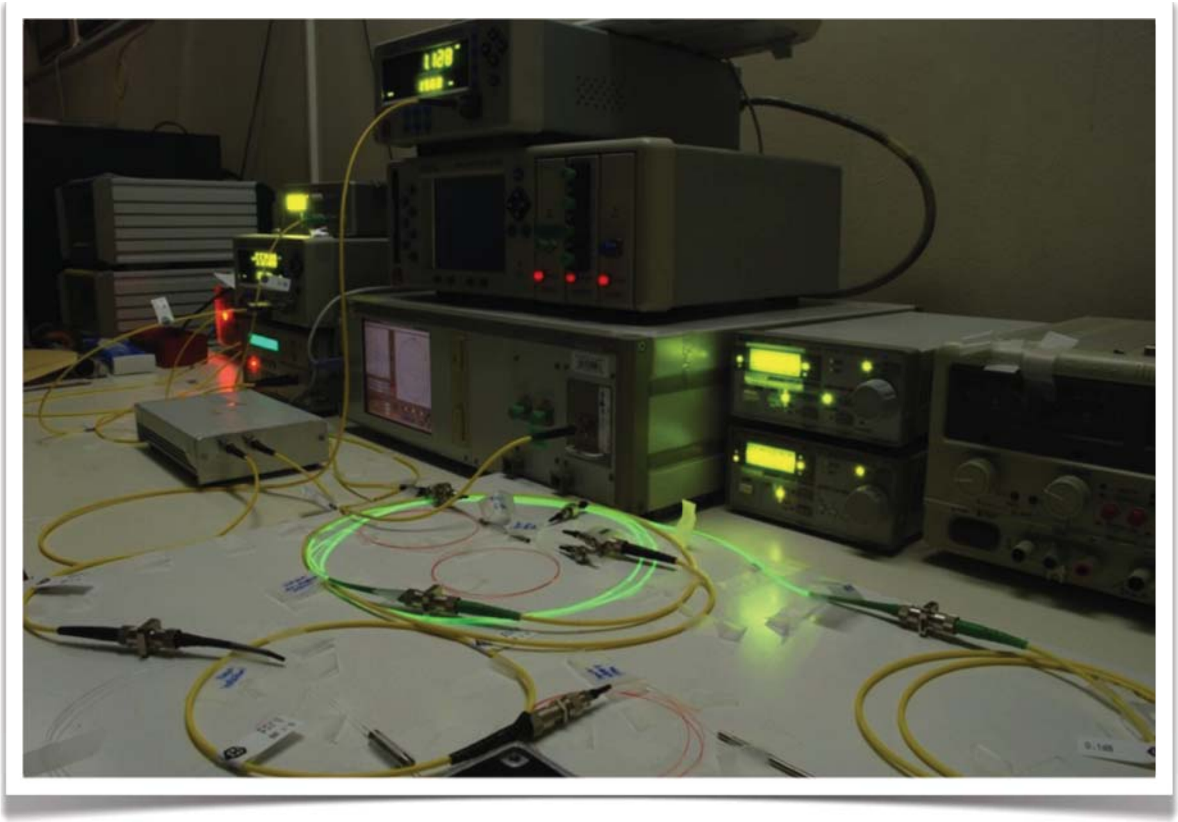


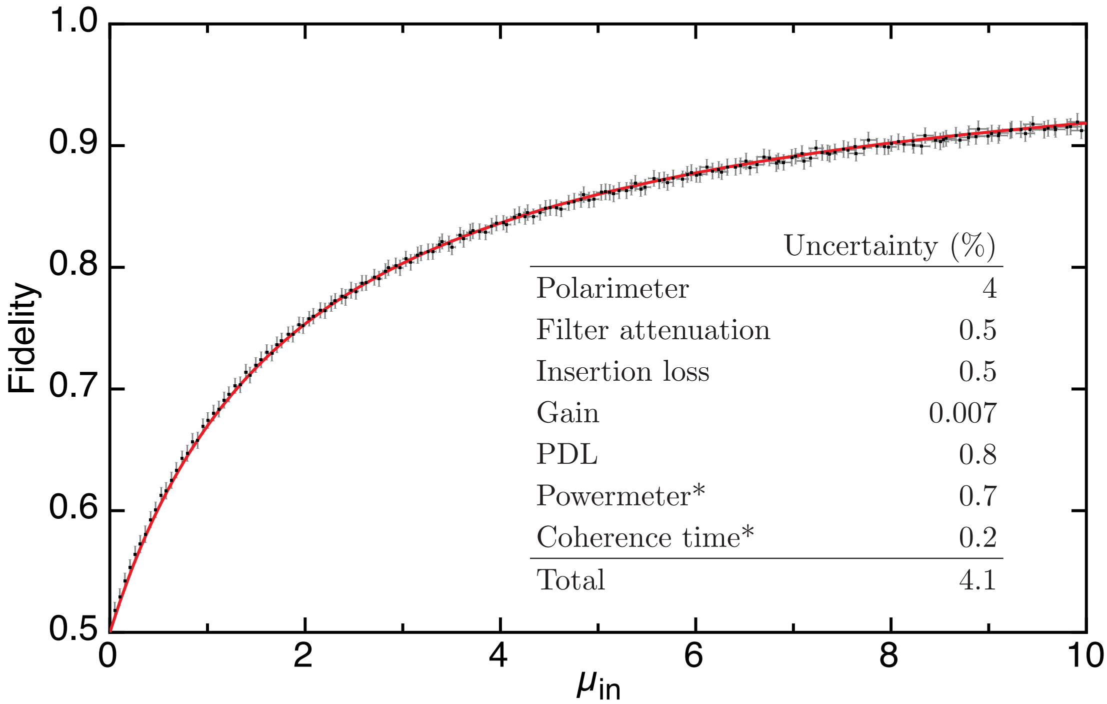
Real setup



Real setup



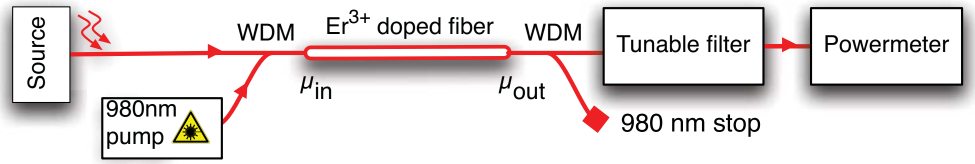




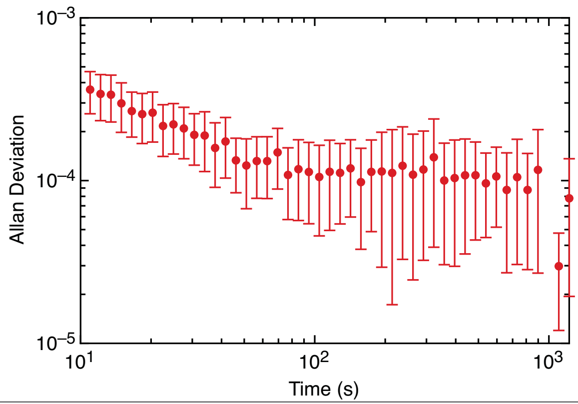
- Absolute measurement
- Agrees with reference to 1.3%
- Works from single photon levels to ~ 0.1μW

Recent improvements

- Simplified the setup



- Stable source to calibrate powermeters
- Long term stability of 10^{-4}
- Measured radiances as low as 0.01 photons/ mode.



Conclusion and Outlook

- This new application of Quantum Physics allows us to measured spectral radiance *absolutely*

- The device is practical
  - Works over a broad power range
  - Precision compatible with industrial applications

- Demonstrates optimal 1 to many cloning $Q = 1.013$

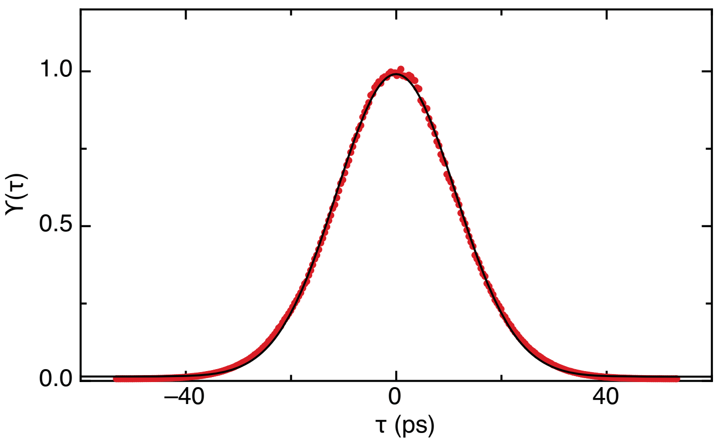
- In collaboration with the PTB the practicality and precision of the device is being improved

Sanguinetti et al. Quantum Cloning for Absolute Radiometry. Phys Rev Lett (2010) vol. 105

Thank you for your attention!

Measurement of the number of modes τ_c^{-1}

- Use a low coherence interferometer for a direct and precise measurement of number of modes



$$\tau_c = \int_{-\infty}^{\infty} |\gamma(\tau)|^2 d\tau,$$

Mandel. Fluctuations of Photon Beams: The Distribution of the Photo-Electrons. Proc. Phys. Soc. (1959) vol. 74 (3) pp. 233-243

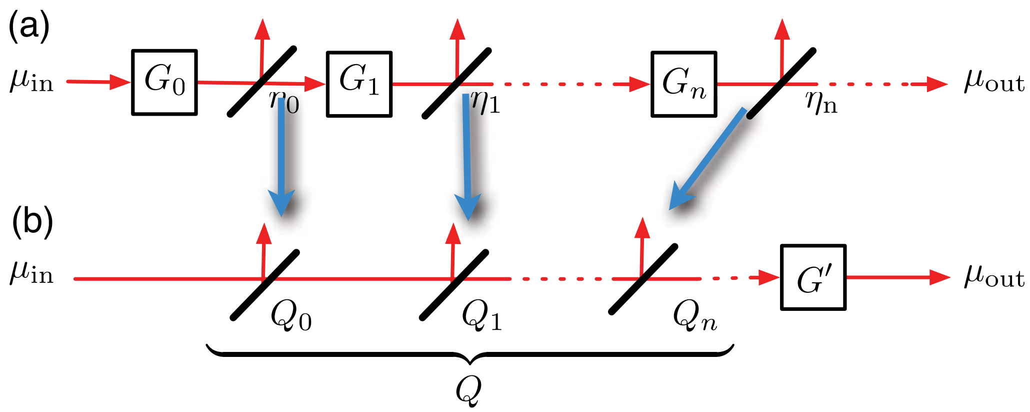
Evaluating uncertainties

Sources of error

- Losses in the amplifier
- Measurement of Fidelity and Gain
- Number of modes per second
- Polarisation dependent loss (PDL)

Losses can be easily modeled

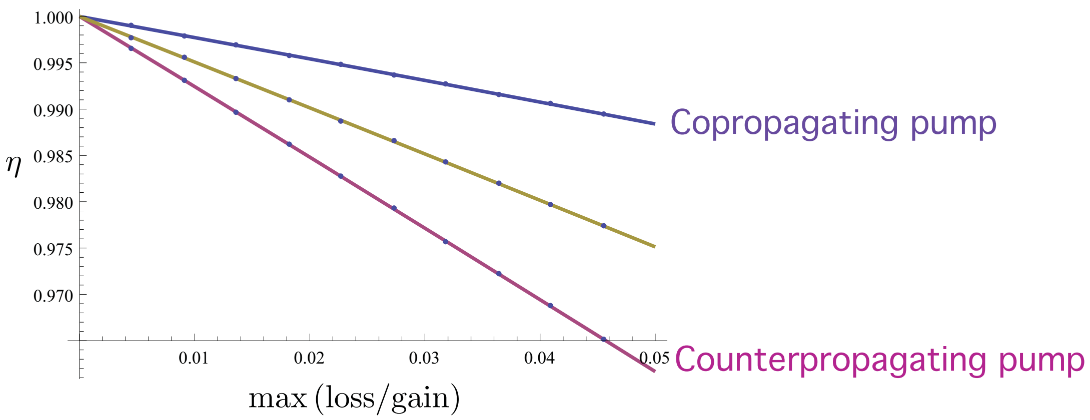
- Imperfect cloning machine can be modeled as optimal cloning machine preceded by losses.

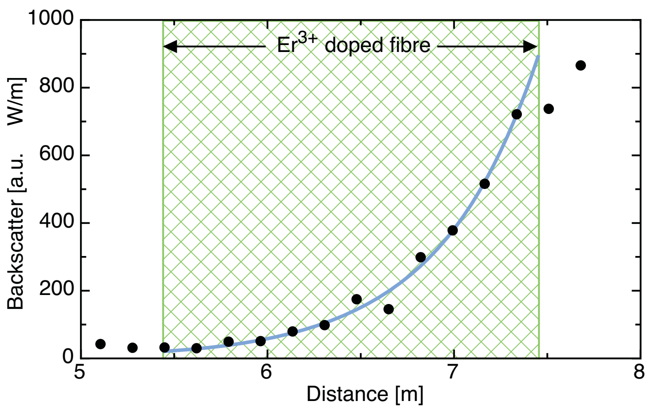


- Parameters Q and G offer a complete description

The effect of losses scales as $1/G$

For a specific inversion profile the effect of losses can be calculated exactly.

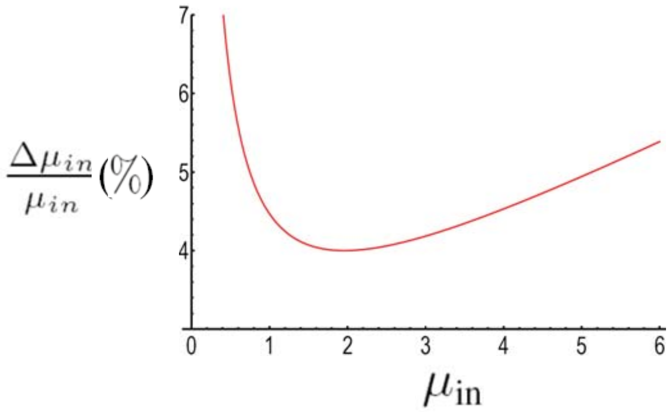


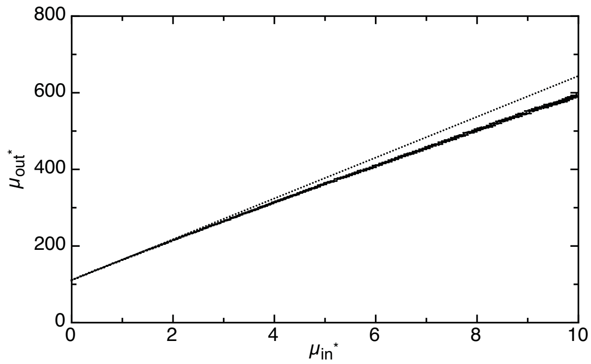


For a gain < 20 dB,
Losses are small.

Error on μ_{in} depends on error in fidelity

$$\Delta\mu_{\text{in}} = (2 + \mu_{\text{in}})^2 \Delta\mathcal{F}.$$

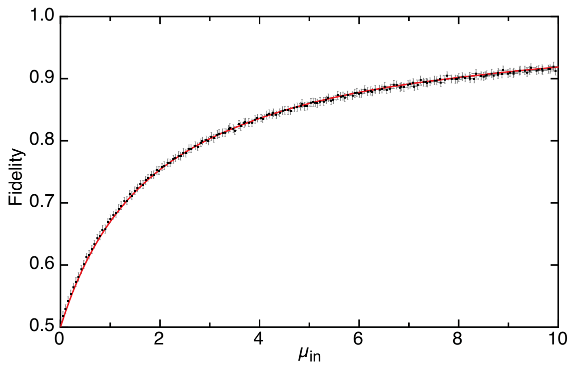


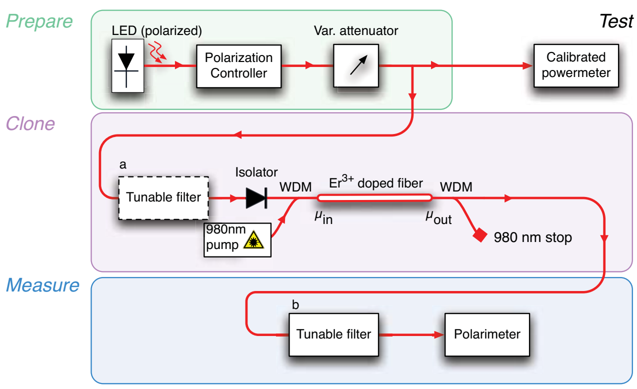


- Precision of absolute measurement has 4 times the error of the relative measurement.
- When the gain is known, ΔF can be very small

Polarisation Dependent Loss can be dealt with by "scrambling"

	PDL (%)
Filter	1
Attenuator	1.4
Powermeter	1.6
Isolator	< 2
WDM	< 2





Overview of errors

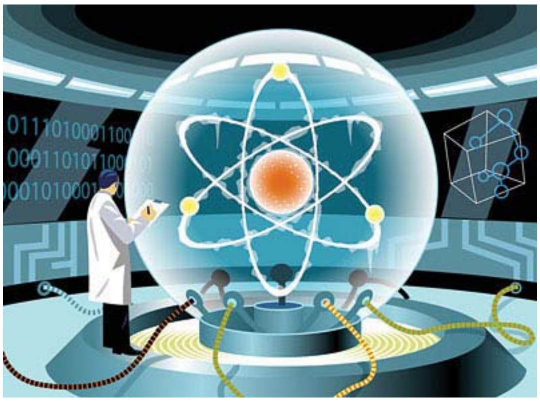
- Dominated by polarimetric uncertainty
- Hard to do better than 0.5%
- Limits are practical, not fundamental.

	Uncertainty (%)
Polarimeter	4
Filter attenuation	0.5
Insertion loss	0.5
Gain	0.007
PDL	0.8
Powermeter*	0.7
Coherence time*	0.2
Total	4.1

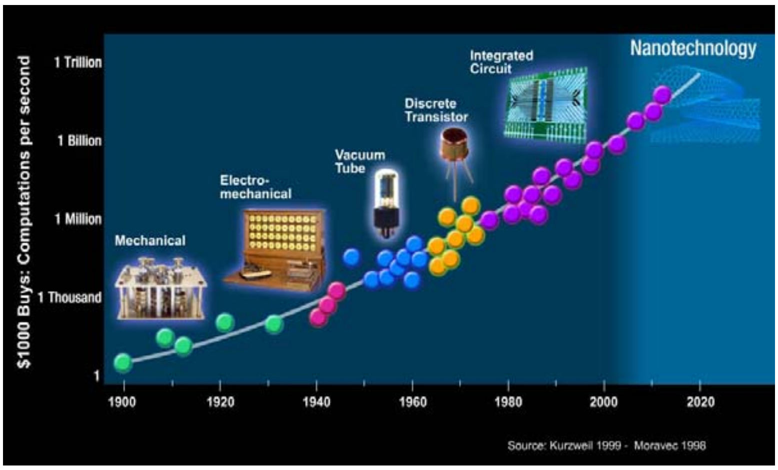
Computing after Scaling

New Computation Paradigms

Bruno Michel, Alessandro Curioni, Walter Riess
IBM Research - Zurich Research Laboratory



Evolution of Information Technology



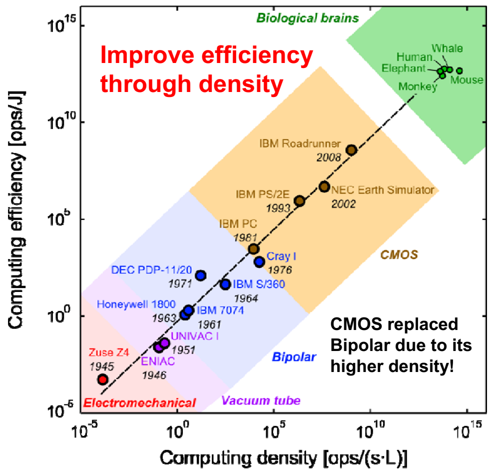
Information technology has prospered by making "bits" smaller.
➔ Smaller = *faster & cheaper (and more efficient)*

- Density and efficiency on log-log line
  - Brain is 10^4 times denser AND 10^4 times more efficient
- Independent of switch technology
  - No jumps mechanical – tube – bipolar – CMOS – neuron
- Communication as main bottleneck
  - Memory proximity lost in current computers (1300 clock access)
  - Detrimental for efficiency

- **Device centric viewpoint (left)**
  ➔ Device performance dominates
  - Power depends on device performance
  - Evolution depends on introduction of better devices

vs.

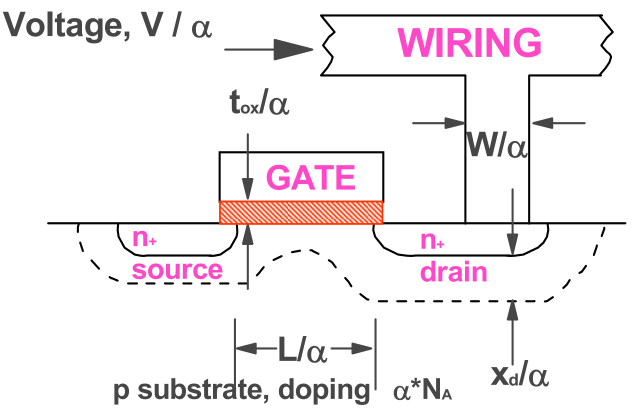
- **Density centric viewpoint (below)**
  ➔ Communication efficiency dominates
  - Power and memory proximity depend on size
  - Evolution depends on denser system
  - Dominant for large systems (>Peta-scale)

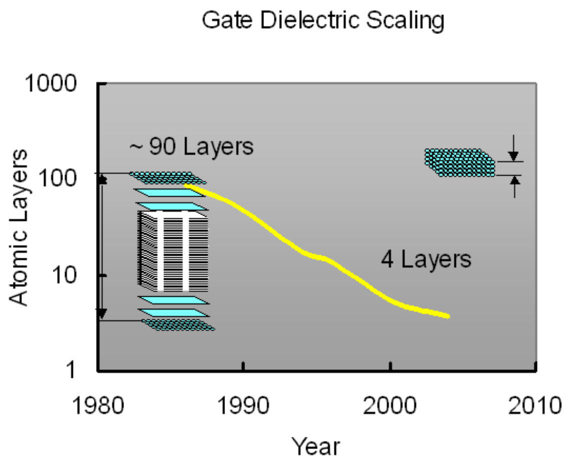


Computing after Scaling - New Computation Paradigms

- **Past**
  - **Dennard scaling of CMOS**
  - **Energy challenges**
- Evolutionary
  - Innovative device scaling and low power devices
  - 3 D packaging
  - Exascale systems: Power, reliability, cost
- Transitional
  - Stepwise introduction – form – function – material
  - Extreme 3D architectures : Volumetric scaling (Form)
  - Zetascale systems: efficiency of communication is key
- Revolutionary - New Computation Paradigms
  - Alternative architecture – neuromorophic computing (Function)
  - Quantum computing
  - DNA computing (Material)
- Challenges

CMOS Device Scaling: Past Enabler of IT Industry





SCALING:

Voltage: V/α

Oxide: t_{ox}/α

Wire width: W/α

Gate width: L/α

Diffusion: x_d/α

Substrate: $\alpha * N_A$

R. H. Dennard *et al.*, *IEEE J. Solid State Circuits*, (1974).

RESULTS:

Higher Density: $\sim\alpha^2$

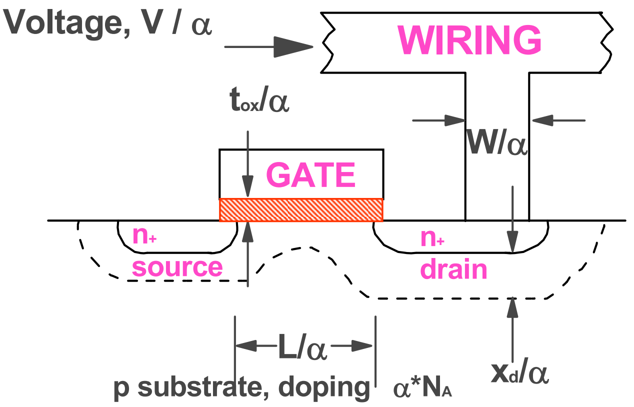
Higher Speed: $\sim\alpha$

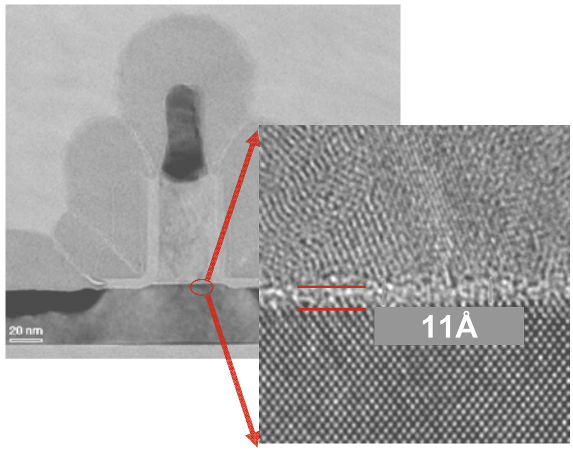
Power/ckt: $\sim 1/\alpha^2$

Power Density: ~Constant

- **Approaching atomistic and quantum-mechanical boundaries**
- Atoms are not scalable!

CMOS Device Scaling: Past Enabler of IT Industry





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Dramatic Rise in Power Density

- **Active power plus passive power**
  - **Gate leakage**
  - **Sub-threshold leakage (source-drain leakage)**

Computing after Scaling - New Computation Paradigms

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  - **Innovative device scaling and low power devices**
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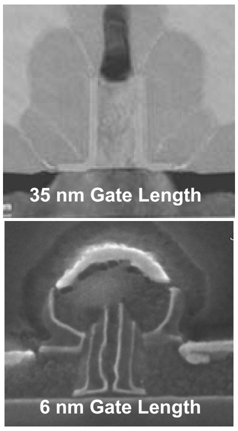
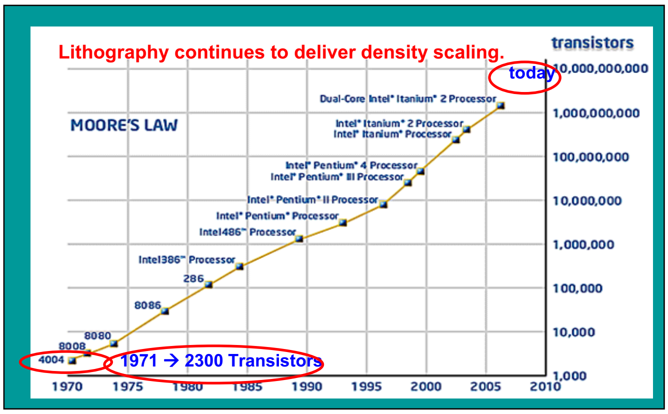
Moore's Law: Materials and device innovation enables future scaling

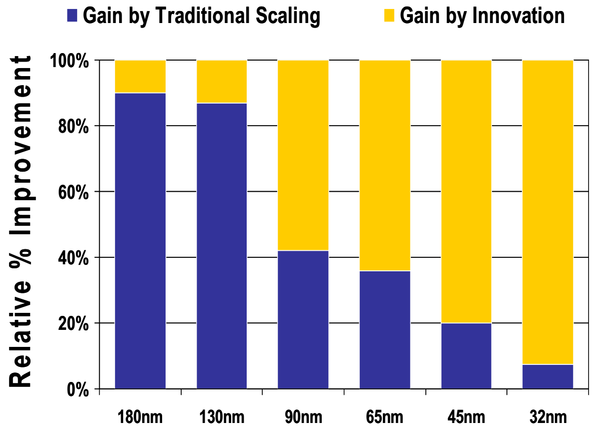


Then	*Now*
▪ Scaling **drove** down cost	▪ Scaling **drives** down cost
▪ Scaling **drove** performance	▪ **Materials, Device Innovation drives** performance
▪ Performance constrained	▪ Power constrained
▪ Active power dominates	▪ Standby power dominates
▪ **Independent** R&D	▪ **Collaborative** R&D

B. Doris et al., IEDM 2002



Source: Intel website



Roadmap of transistor scaling will continue below 10 nm node

3D will offer new dimension of scaling ➔ Moore's law goes 3D

Towards Ultimate Device Scaling & How to Reach Low V_{dd}

1. Avoid short channel effects (SCE): $L_G \geq 4\lambda$

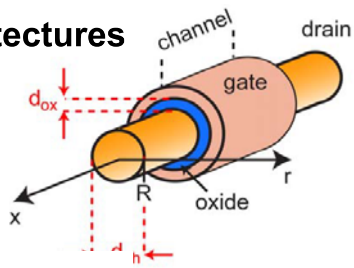
λ depends on Materials & Device Geometry

$$\lambda = \sqrt{\frac{\varepsilon_{\mathrm{ch}}}{\varepsilon_{\mathrm{ox}}} d_{\mathrm{ox}} d_{\mathrm{channel}}}$$

Ultra-thin d_{channel}	Ultra-thin d_{ox}	high-k dielectrics	Ge / III-V
$\lambda \downarrow$	$\lambda \downarrow$	$\lambda \downarrow$	$\lambda \uparrow$

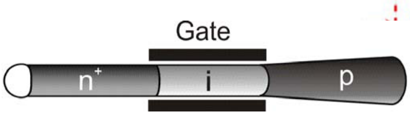
2. Exploit the potential of novel materials & device architectures

➔Surround Gate for optimum electrostatic control



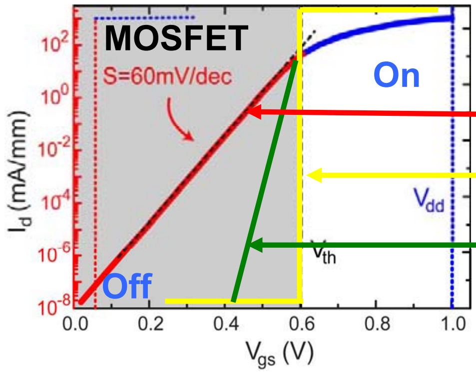
3. New Device Mechanisms – Steep Slope Devices

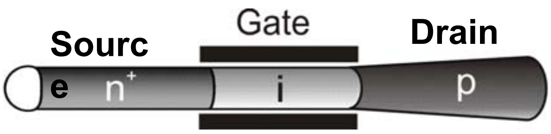
➔Tunnel FET for S < 60 mV/dec



Steep Sub-Threshold Slope Switch

- Steep turn-on characteristics S essential for low-power devices

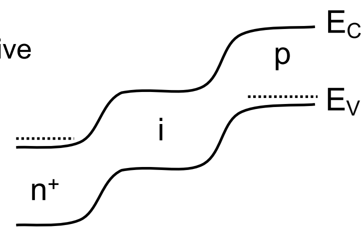




- **Tunnel FET:**
  Gated ***p-i-n*** structure (p-type tunnel FET)
- **Reverse bias:** band-to-band-tunneling (BTBT)

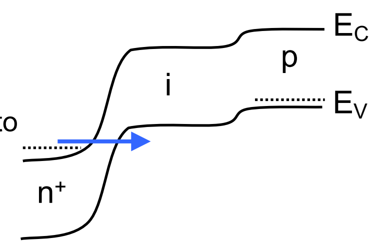
OFF state

- V_{DS} = negative
- V_{GS} = 0V
- No current flows

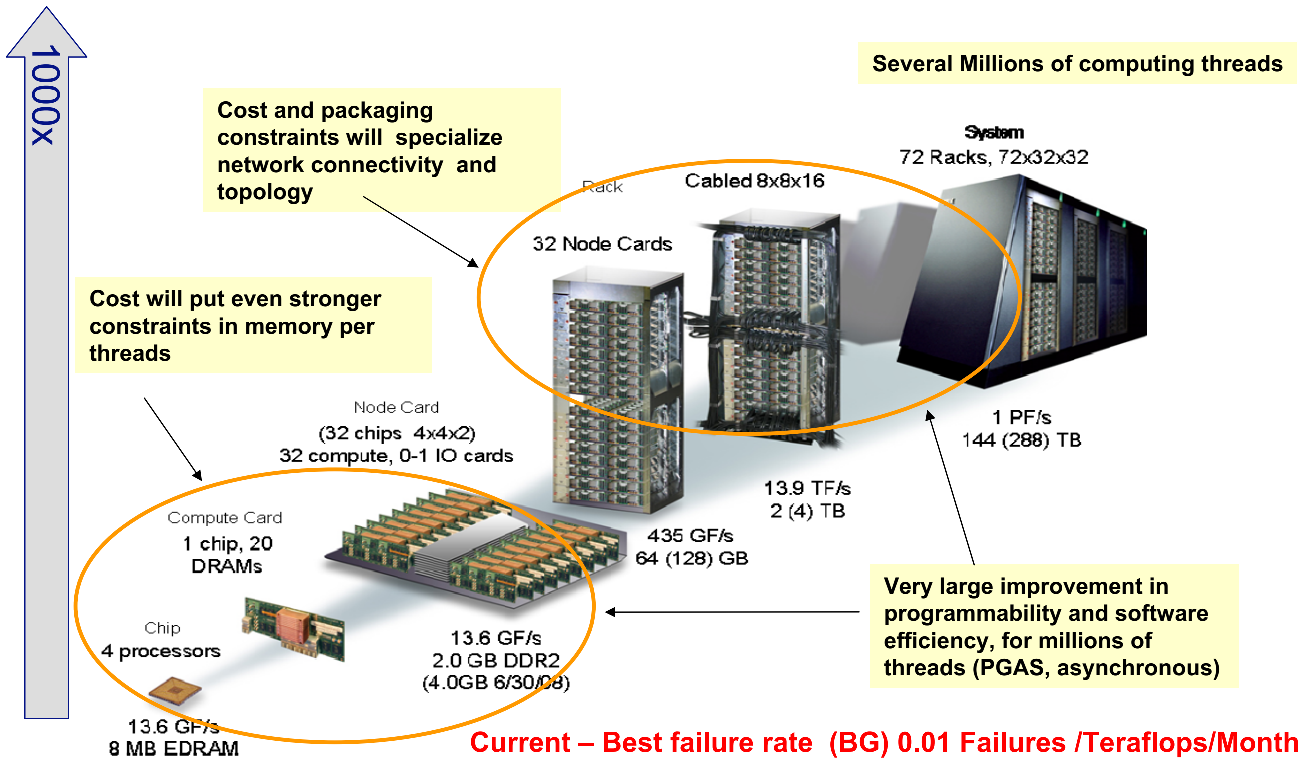


ON state

- V_{DS} = negative
- V_{GS} = negative
- Holes are injected into the channel via BTBT



Deep Computing Research: (20MWatts vs 2GWatts)
Exascale: Innovation demanded by power, cost and usability



Current – Best failure rate (BG) 0.01 Failures /Teraflops/Month

1 Failure every 4 Minutes at Exaflop

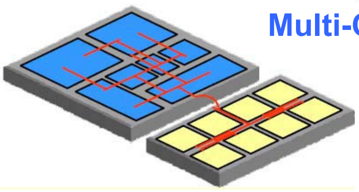
Computing after Scaling - New Computation Paradigms

- Past
  - Dennard scaling of CMOS
  - Energy challenges
- Evolutionary
  - Innovative device scaling and low power devices
  - 3 D packaging
  - Exascale systems: Power, reliability, cost
- **Transitional**
  - **Stepwise introduction – form – function – material**
  - **Extreme 3D architectures : Volumetric scaling (Form)**
  - **Zetascale systems: efficiency of communication is key**
- Revolutionary - New Computation Paradigms
  - Alternative architecture – neuromorophic computing (Function)
  - Quantum computing
  - DNA computing (Material)
- Challenges

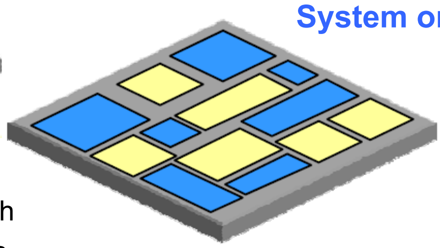
Paradigm Change: Vertical Integration

Brain: synapse network

Multi-Chip Design



System on Chip

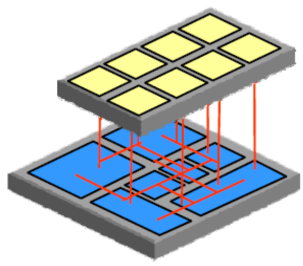


Benefits:

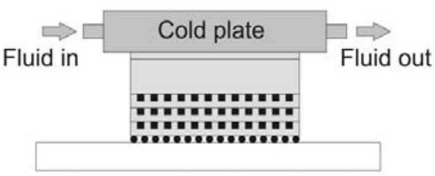
- High core-cache bandwidth
- Separation of technologies
- Reduction in wire length

→ Equivalent to two generations of scaling

→ No impact on software development



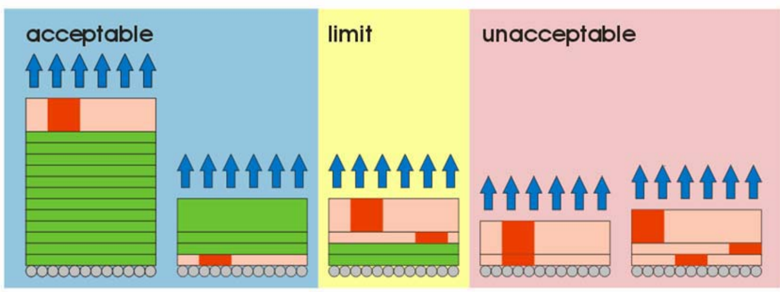
3D Integration



Microchannel back-side heat removal

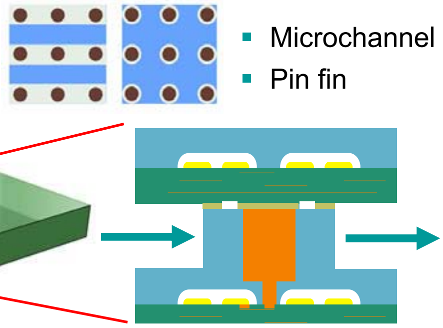
➔ Heat removal limit constrains electrical design

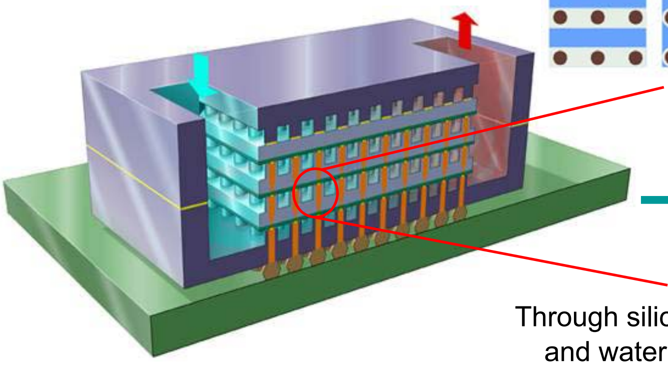
Global wire lengths reduction



Scalable Heat Removal by Interlayer Cooling

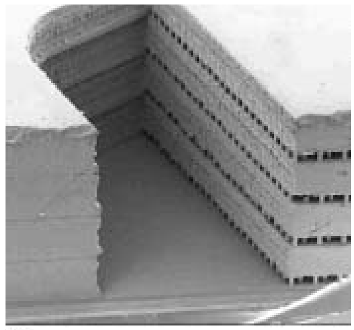
- 3D integration requires interlayer cooling for stacked logic chips
- Bonding scheme to isolate electrical interconnects from coolant



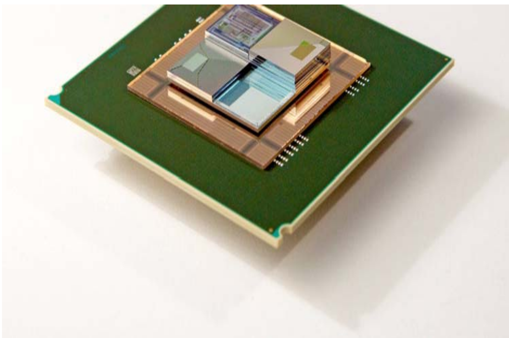


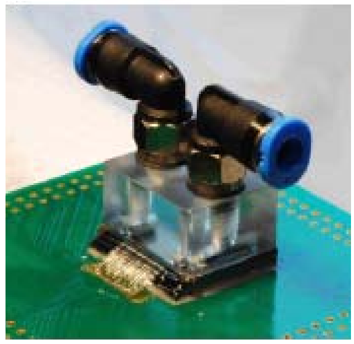
Through silicon via electrical bonding and water insulation scheme

cross-section through fluid port and cavities



- A large fraction of energy in computers is spent for data transport
- Shrinking computers saves energy

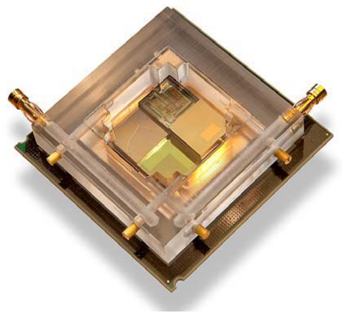


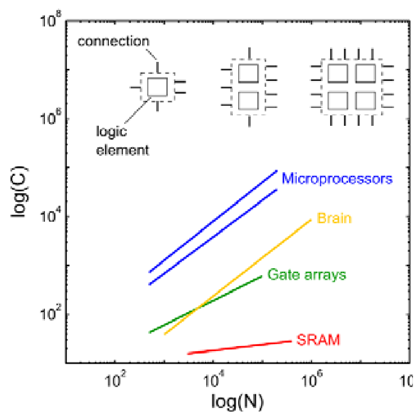


Test vehicle with fluid manifold and connection

Why Size Matters for Computers

- Today's systems: Transistors occupy only 1ppm of the system volume – ~1'000'000ppm power supply & cooling
  ➔ Never before devices occupied a smaller volume fraction
- PC AT used about same amount for computation and communication
  – Since then processor became 10'000 times better
  – PCB and C4 interface only improved 100 times
- Majority of Energy used for data transport in current computers
  – 99% communication and 1% computation
  – 1300 clock cycles needed for main memory access
- Major reason C4 bottleneck that creates "memory wall"
  – 3D integration moves main memory into chip stack
  – "Cooling wall" is solved by interlayer cooled chip stacks
- Brain serves as example for dense and efficient computing
  – 3D integration and memory proximity is key for efficiency
  – Brain has similar Rentian slope as microprocessors
  – Brain communication density lower for 1 neuron = 1000 transistors





$$N_{conn} = k N_{gates}^{p}$$

Rent exponent

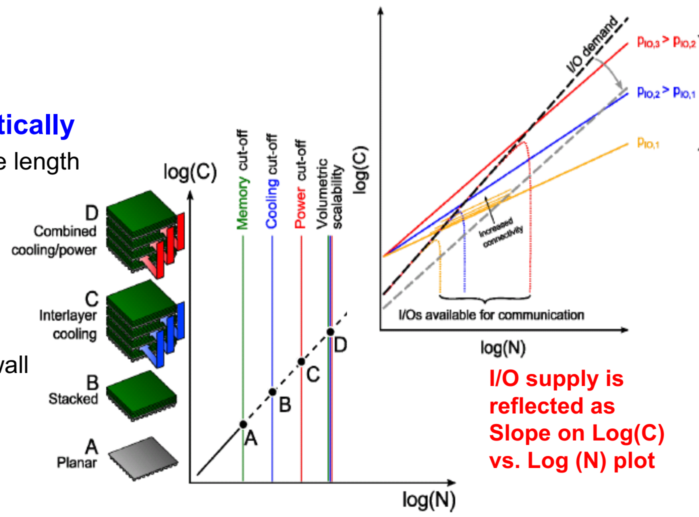
Number of connections

Number of gates

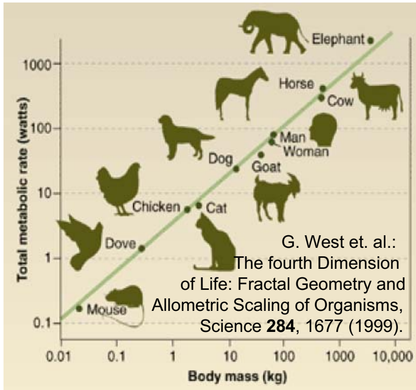
Average number of connections per gate

Density Improves Efficiency

- **Communication energy dominates quadratically**
  - Power and memory proximity dependent on wire length
  - Communication energy scales faster than size
- **Memory proximity restored in chip stack**
  - Main memory in stack – no cache necessary
  - Interlayer cooling removes cooling wall
  - Electrochemical power supply removes power wall
- **Reach density AND efficiency of brain**
  - CMOS technology can reach sufficient density
- **Key volumetric scaling laws**
  - Device count AND power demand scale with volume
  - Communication AND power supply scale with surface
  - Large-system performance scales with Hypersurface / Hypervolume = 1-D / D
- **Biological (allometric) volumetric scaling**
  - Allometric scaling: Exponent 0.75 ➔ 4 D scaling
  - Why? Chemical power supply and hierarchical supply networks
  - Fluid pressure drop scales 4-dimensional

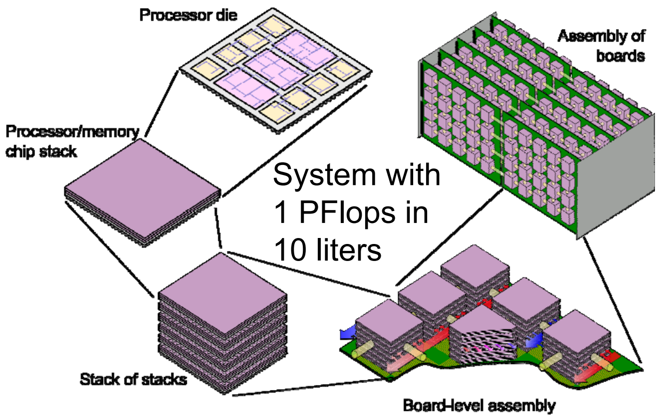


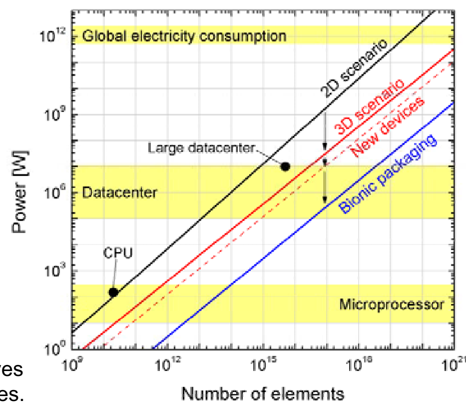
I/O supply is reflected as Slope on Log(C) vs. Log (N) plot

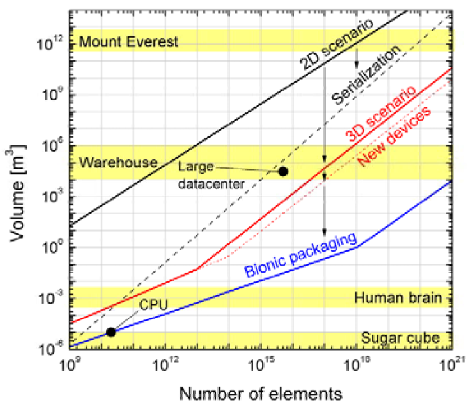


Scaling to 1 PFlops in 10 Liters

- **Efficiency comparison**
  - 1PFlops system currently consumes ~10MW
  - Proposed 0.1 PF ultra-dense system consumes 5kW
  - Conventional power supply scales causes power supply wall
- **Extreme 3D 1PFlops ultra-dense system**
  - Stack ~10 layers of memory on logic
  - Stack several memory-logic stacks to stack of stacks
  - Combine several blocks of stacks to MCM (MBM)
  - Combine MCMs to high density 3D system
- **Key enabling technologies**
  - Interlayer cooling
  - Electrochemical chip power supply
- **Impact**
  - 5'000x smaller power
  - 50'000'000x smaller volume
  - Scalability until zetascale system







P. Ruch, T. Brunschwiler, W. Escher, S. Paredes, and B. Michel, "Towards 5 dimensional scaling: How density improves efficiency in future computers", IBM J. Res. Develop. (Centennial Issue) in press.

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  - **Quantum computing**
  - **DNA computing (Material)**
- Challenges

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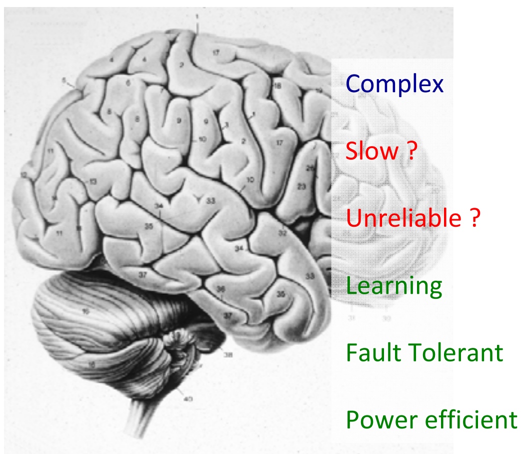
Brain Inspired Computing

- Brain inspired, non-von Neumann architecture
- Use of CMOS and attractive for nanoelectronics
- Key features : Universality, scalability, fault tolerance, power efficiency, speed, learning
- Application : Downscale complexity and discover computational principles

Computer

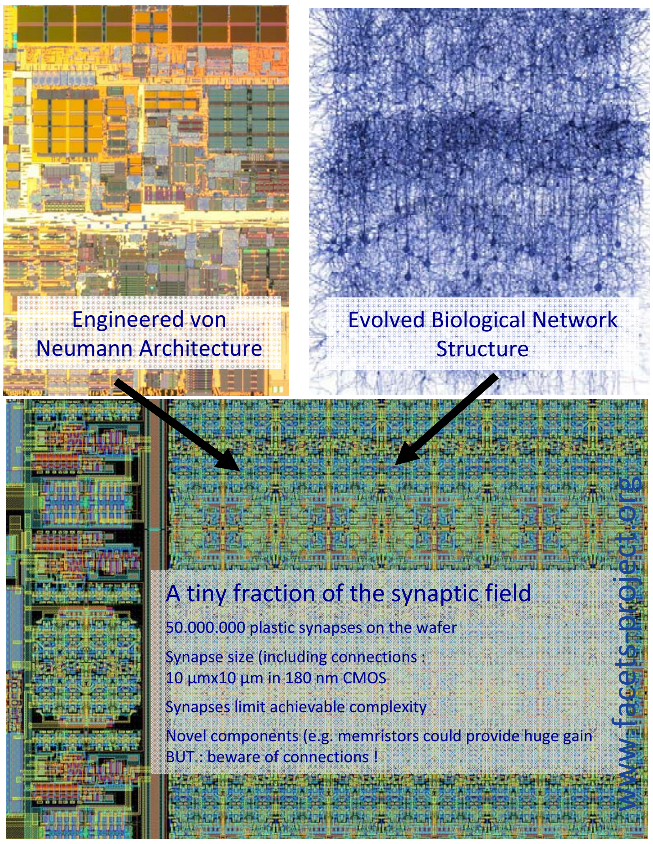
vs.

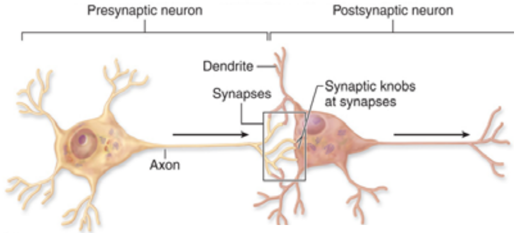
Human
in
Chess and
Jeopardy



A Systems View

Neuromorphic Computing

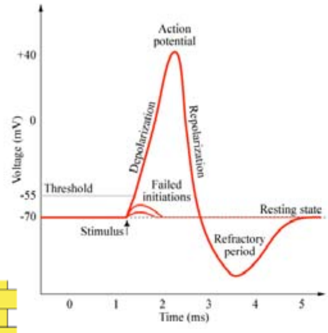


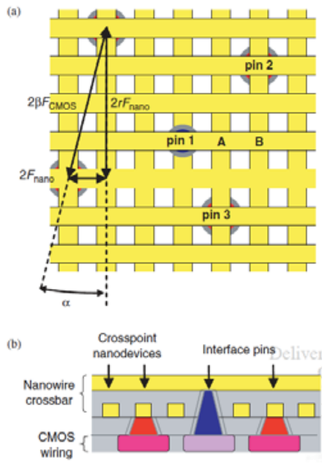


$$C\frac{dV(t)}{dt} = -g\,(V(t)-U)$$

"Spikes" as Computational Primitives

Result of charge integration





Take the best of both worlds : CMOS **fidelity** + Nanoscale **density**

2 Terminal Cross-Point Devices

Nanowire Cross Bars on Top of conventional CMOS devices

>1000-fold synaptic density

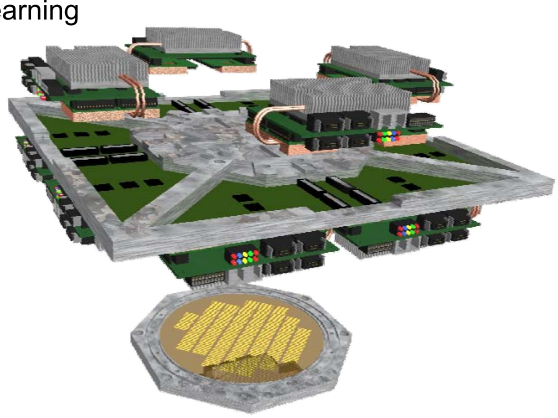
>1000 fold communication bandwidth requirement !

Speed vs. Density

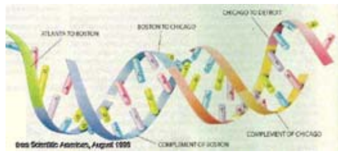
K. Likharev, J. Nanoelectronics and Optoelectronics, Vol.3, 203–230, 2008

Applications

- **Neuroscience Research Tool**
  - Exploit range of relevant time scales and speeds
  - Develop theories for development, learning, and plasticity
  - Transfer results to neuromedicine, neuropharmacy, neuropsychology
- **Large Scale System Demonstrator for Nanoscale Devices**
  - Exploit small size – tolerate imperfections and lack of precision
  - Approach $>10^{15}$ dynamic storage cells (synapses)
  - Transfer results to solid-state manufacturing
- **Novel Computing Architecture**
  - Exploit low power, scalability, speed, fault tolerance, learning
  - Process noisy, unexpected data to make predictions
  - Transfer results to process non-biological information
- **Downscale to Low-Cost, Low-Power Devices**
  - Exploit results on principles of neural computation
  - Simplify circuits for consumer oriented applications
  - Transfer to low-cost, low-power consumer appliances

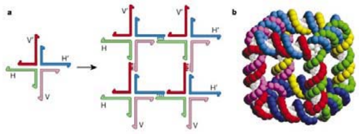


Biomolecular (DNA) Computing



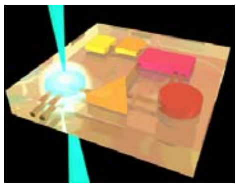
Present Status

- Quickly advancing DNA processing & analyzing techniques
- Adleman incorporated computation into assembly of DNA strands
- Theories: Strand assembly, Wang tiles, and turing machines
- Recent experimental demonstration of full 4 bit square root "digital" DNA circuit



Present Challenges

- Evolving algorithmic paradigms for universal DNA computation
- Efficient error resistant separations (word designs with high efficiency and specificity)
- Moderate scalability of current approaches with too much molecules used in parallel

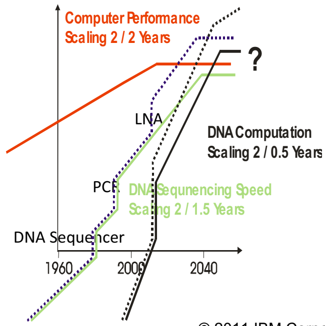


Potential of the Technology

- Volume: 10^{21} bases/liter or 10^{18} processors/liter
- Speed: > 1 ExaOp/s in a cm^3 vs. 10^4 Op/s in a cm^3 of current computer
- Efficiency: 10^{-18} Joules per Op vs. 10^{-12} for conventional computers
- Strengths: Huge memories, massively parallel operation, associative searches
- Weaknesses: Error, slow Input/Output, difficult programming and integratio

Possible Impact

- Efficient fast solving NP-complete problems and associative searches
- Radically smaller system volume and higher storage density



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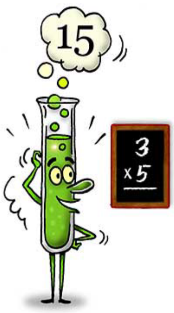
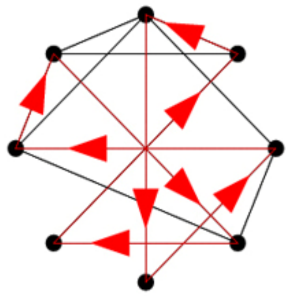
Why Quantum Computing?

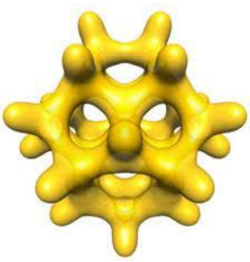
A quantum computer can solve interesting problems requiring fundamentally fewer computational steps than any classical computer



Potential Impact

- Cryptanalysis
  - Routine decrypt all present and past transmissions
- General Purpose Optimization — applications to databases
  - Sub-exponential advantage available using quantum algorithms for all existing optimization algorithms
- Powerful Quantum Simulations—applications to bio-pharma; material/molecule design
  - Many-atom simulations– create a new era of materials design!

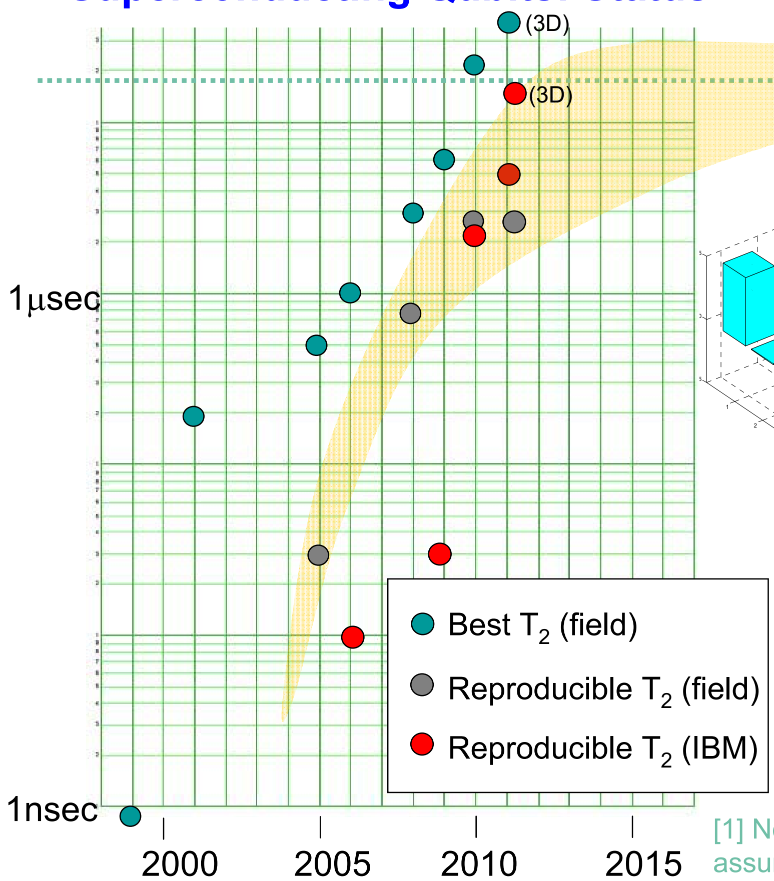


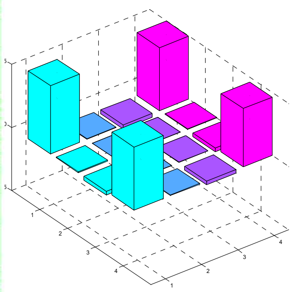


Quantum Computing Approaches – not complete ....

Approach	Progress on key metrics	Obstacles to be overcome
Superconducting devices	Rapidly improving coherence times and gate fidelities, realistic system concepts	Complexity of low-temperature operation, improvement in materials properties, ...
Electronic Quantum dots	Good coherence times achieved, poor gate fidelities so far	Complexity of low-temperature operation, unavailability of workable qubit couplers, ...
Ion traps	Best coherence times and good gate fidelities, several-qubit functionality demonstrated	complex optical control, slow clock speed, ...
Neutral atom traps	Very good coherence times, rudimentary qubit functionality demonstrated	complex optical control, weak, unreliable trapping, good fidelity gates not demonstrated
Diamond NV centers	Optical manipulation of high-coherence single qubits with moderate fidelity	no workable multi-qubit architecture proposed, ...
Topological quantum computing	Workable topologically protected qubit has not been seen in the lab	The fundamental theoretical physics must be confirmed by experiment, ...

Superconducting Qubits: Status





- Entangled state fidelity ~97-99%
- CNOT gate fidelity ~93%
- Single qubit fidelity ~99.6%
- Fidelity ~99.9% required for fault-tolerance
- Concise plans for further improvements in place
- Architecture exist

⇒ Two-qubit operations with >98% fidelity within reach; begin considering system architecture!

[1] Noise threshold for 2D fault tolerant computation assuming 30ns gate time

Challenges

- **What are the strengths of quantum computing?**
- **Which problem can a quantum computing solve in the near future?**
  - 500 perfect qubits: factor a 50 decimal digit number!
  - Imperfect qubits requiring 50 physical qubits per logical qubit – factor a 1 decimal digit number
  - Error correction may initially require 100’s of physical qubits to get one logical qubit.
  - Better hardware requires less overhead but error bars on resources are huge!
- **Are there smaller systems with imperfect qubits that are good stepping stones?**
  - Quantum repeaters
  - Quantum control systems
- **Need convincing target application**
  - Government interest totally centered on factoring
  - Are there interesting business applications?
  - Algorithms – computer science
- **Technology Approach**
  - Which quantum computing approach looks most promising?
    - Fastest rate of progress?
    - Biggest potential?
- **Von Neumann and non Von Neumann will coexist**
  - What is the interface to Von Neumann computers?
  - What technology will work on which problem?

Summary

- **Computer efficiency increased by 10 orders of magnitude since 1945**
  - Main drivers: Transistor, IC, and VLSI, device drive slows down
  - 9 orders left until kTln2 (6 orders realistic with dissipative components)
- **Evolutionary**
  - Innovative device scaling and low power devices can provide 20x efficiency improvement
  - Exascale systems: 50x efficiency missing ➔ 3 D packaging (50x efficiency improvement)
- **Transitional**
  - Extreme 3D architectures : Volumetric scaling ➔ 5’000 x improved efficiency
  - Combination may allow Zetascale systems with sizable power demand (< 1GW)
- **Revolutionary - New computation paradigms**
  - Alternative architecture – neuromorophic computing
  - Quantum computing
  - DNA computing
- **Key questions for all new computation paradigms**
  - Unique impact needed
  - Entry-level system needed
  - What is the roadmap and the window of opportunity
  - Many more open questions ……

Thank you for your attention

Questions?

Mesoscopic atomic superposition states for metrology and quantum information

Jürgen Appel,
S. Lund-Christensen, J.B. Beguin, P. Windpassinger, D. Oblak, J. Renema,
A. Louchet-Chauvet, N. Kjærgaard and E.S. Polzik

Niels Bohr Institute
University of Copenhagen, Denmark

6.9.2011
Quantum Information Processing and Communication (QIPC)
Zürich

DET NATURVIDENSKABELIGE FAKULTET
KØBENHAVNS UNIVERSITET

Abstract Submitted to the International Conference on Quantum Information Processing and Communication (QIPC) 2011

Mesoscopic atomic superposition states for metrology and quantum information

J. Appel[1], S. Lund-Christensen[1], J.B. Beguin[1], P. Windpassinger[2], D. Oblak[3], J. Renema, A. Louchet[4], N. Kjærgaard[5], E. Polzik[1]

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[3] Present address: IQIS, University of Calgary, 2500 University Drive NW, T2N 1N4 Calgary, Alberta

[4] Present address: LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 avenue de l'Observatoire, 75014 Paris, France.

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Neutral atoms are a well understood, controllable, "clean" physical system and due to the identical electronic structure of each atom the coupling between light and matter can be easily enhanced by using ensembles.

Since the collective quantum state of the atoms is entangled with a light pulse propagating through and emerging from such an ensemble, by measuring the optical state and its quantum fluctuations, quantum noise limited measurements of the atomic state can be performed: optically dense atomic ensembles can be used for metrology as sensitive field sensors or for atomic clocks with a precision beyond the standard quantum limit.

Using shot noise limited Quantum-Non-Demolition measurements we prepare an entangled and spin squeezed ensemble of 10^5 cold Cs atoms [1] which we use to improve the precision of an atomic clock by $> 1\,\mathrm{dB}$ beyond the projection noise limit [2].

Non-Gaussian states are a valuable resource for quantum information and computation. We report on progress towards applying our method for realizing and characterizing such atomic states by performing a non-Gaussian measurement on the entangled light pulse and on using an ensemble of laser cooled atoms trapped along a nano-fiber [3].

[1] J. Appel *et al.*, *Proceedings Of The National Academy Of Sciences*, **106**:10960–10965, June 2009.

[2] A. Louchet-Chauvet *et al.*, *New Journal Of Physics*, **12**(6):065032–+, June 2010.

[3] E. Vetsch *et al.*, *Physical Review Letters*, **104**(20):203603–+, May 2010.

[X] Invited Talk
[ ] Prefer Contributed Oral Presentation
[ ] Prefer Poster Presentation

Jürgen Appel
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Topic: Atomic systems