



Status of the Nanoelectronic Modeling tool (NEMO 1-D and 3-D) and its planned extension to Spintronics

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Work performed in collaboration with
Fabiano Oyafuso, R. Chris Bowen, Tom Cwik (JPL)
Tim Boykin (U Alabama in Huntsville)

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology,
under a contract with the National Aeronautics and Space Administration



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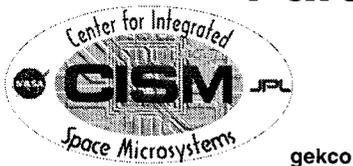




Presentation Outline



- **NASA Mission Pull**
- **Technology Push:**
- **What is a Quantum Dot ?**
- **Our Project portfolio**
 - Modeling / Characterization / Applications
- **Quantum Dot Modeling:**
 - Tight Binding Parameterization
 - Strain
 - Alloy Disorder
 - Interface Interdiffusion
- **NEMO 3-D:**
 - Parallelization, Nanotubes, GUI





2004-2015 Mission Pull



Solar System Exploration near-term

- Pluto (04)
- Europa orbiter (06)
- Solar Probe (07)

Solar System Exploration long-term

- Comet nucleus sample return
- Europa lander
- Titan explorer

Structure and Evolution of the Universe (SEU)

- 14 projects

Sun Earth Connection (SEC)

- 10 projects

General Technology Requirements

- High radiation tolerance
- Extreme temperature operation
- Low weight, low power, high performance, high capacity

Defined IT Requirements

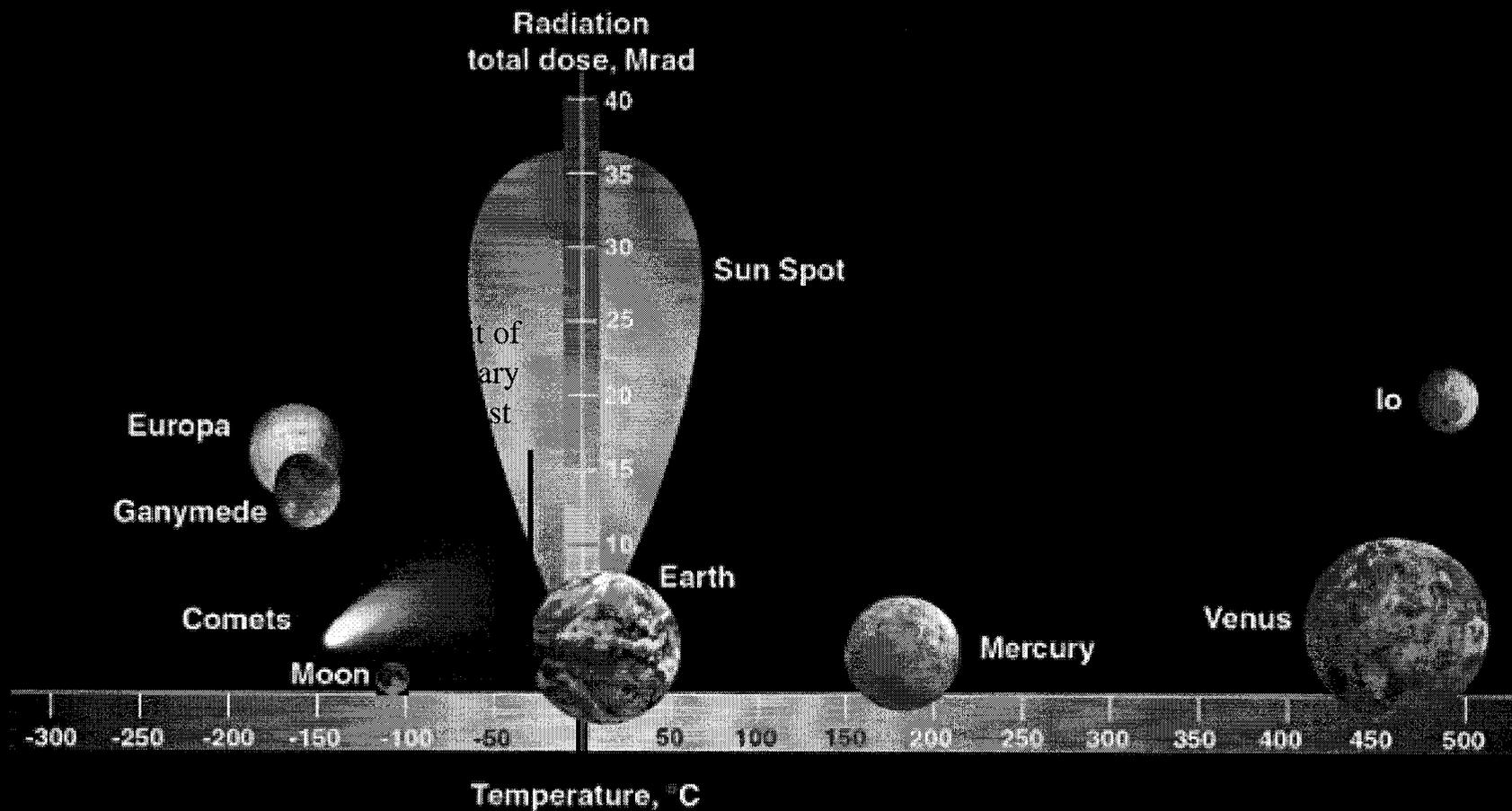
- Closed loop autonomous Guidance Navigation and Control
- Formation flying
- Data Fusion
- Data Timing Synchronization
- Science feature detection
- Science alert capability
- Data synthesis and visualization

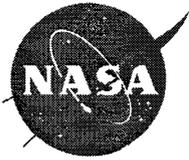


NASA missions require systems that currently do not exist

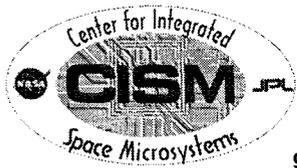
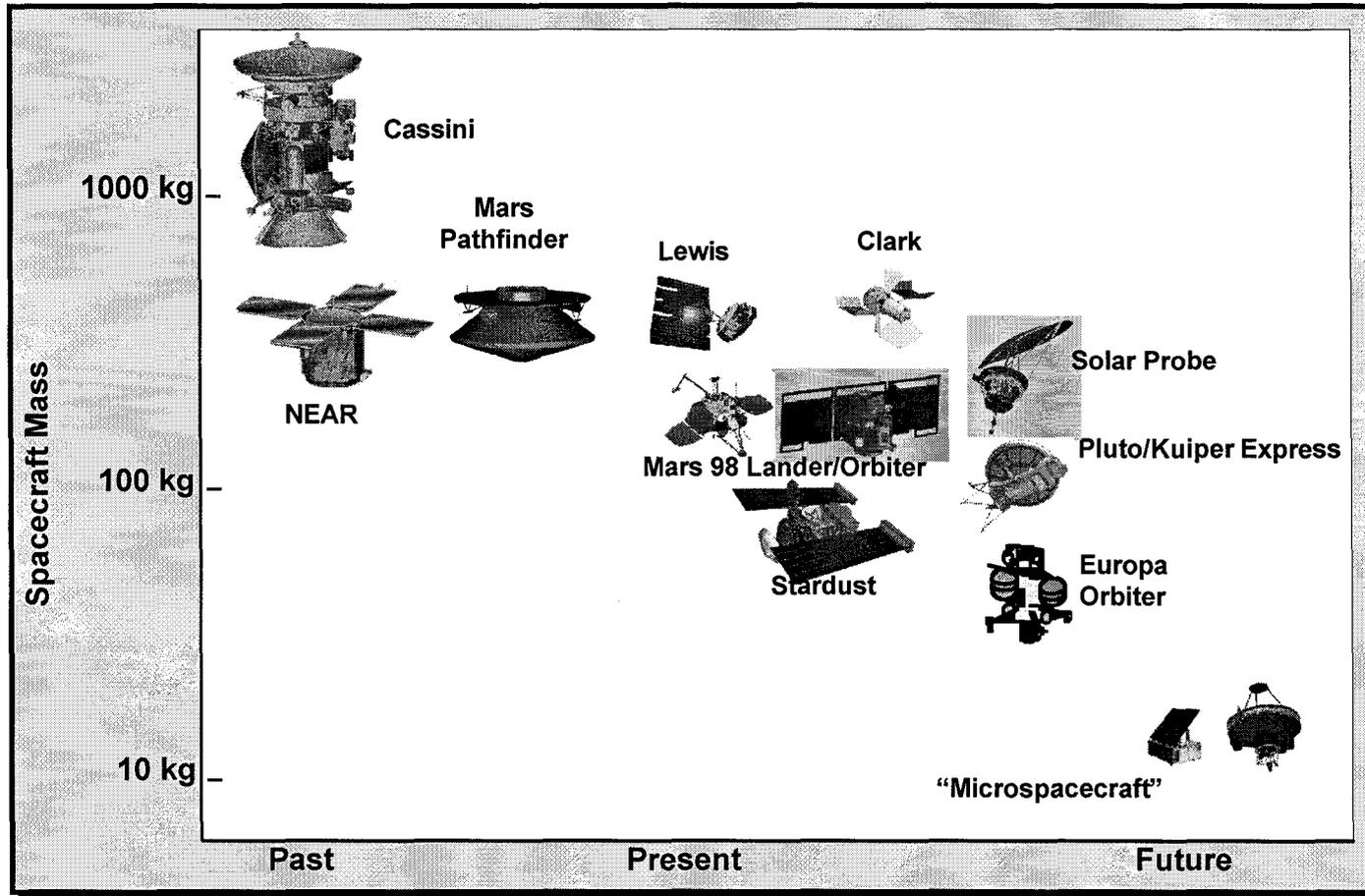


Planetary Extreme Environments





Progressive Spacecraft Miniaturization **JPL**



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*Low weight, low power and high efficiency
Have a special meaning to NASA*





Technology Push Toward Fundamental Limitations



Commercial market pushes computing performance (FLOPS/weight/power):

- Enabled by device miniaturization
- Enabled by chip size increase
- Limited by: Costs of fabrication
- Limited by: Discrete atoms/electrons

Additional NASA Requirements:

- High radiation tolerance
- Extreme temperature operation-hot/cold





Technology Push



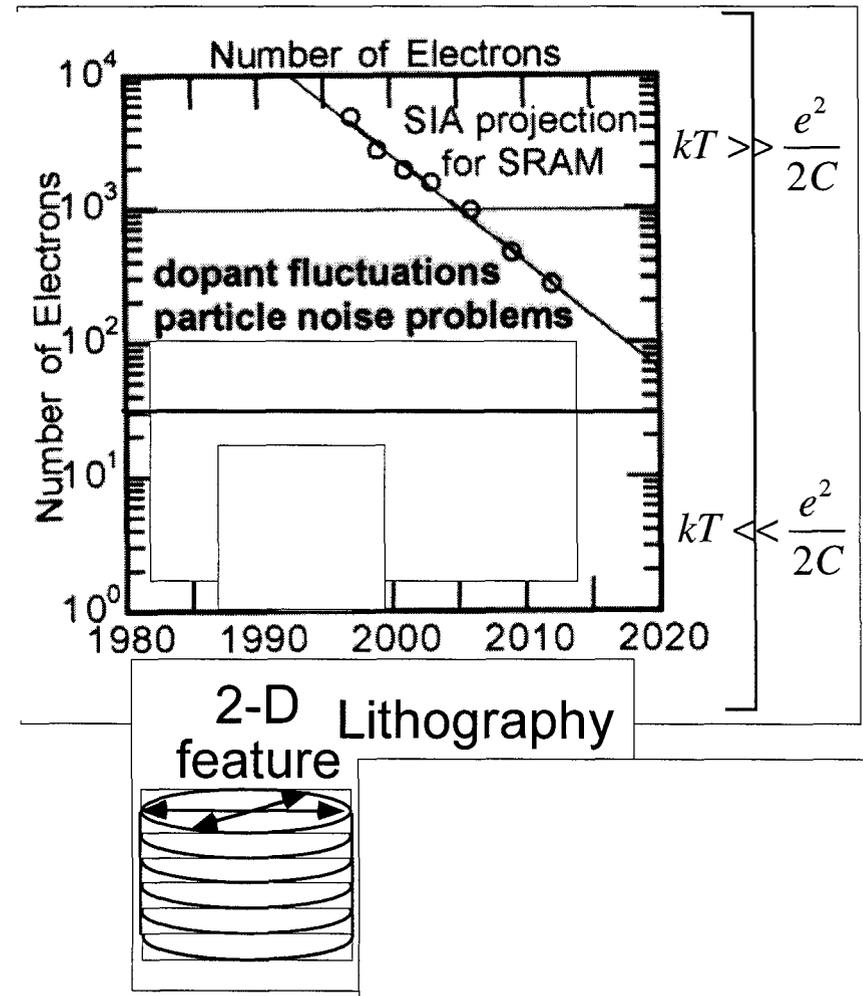
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Technology Push



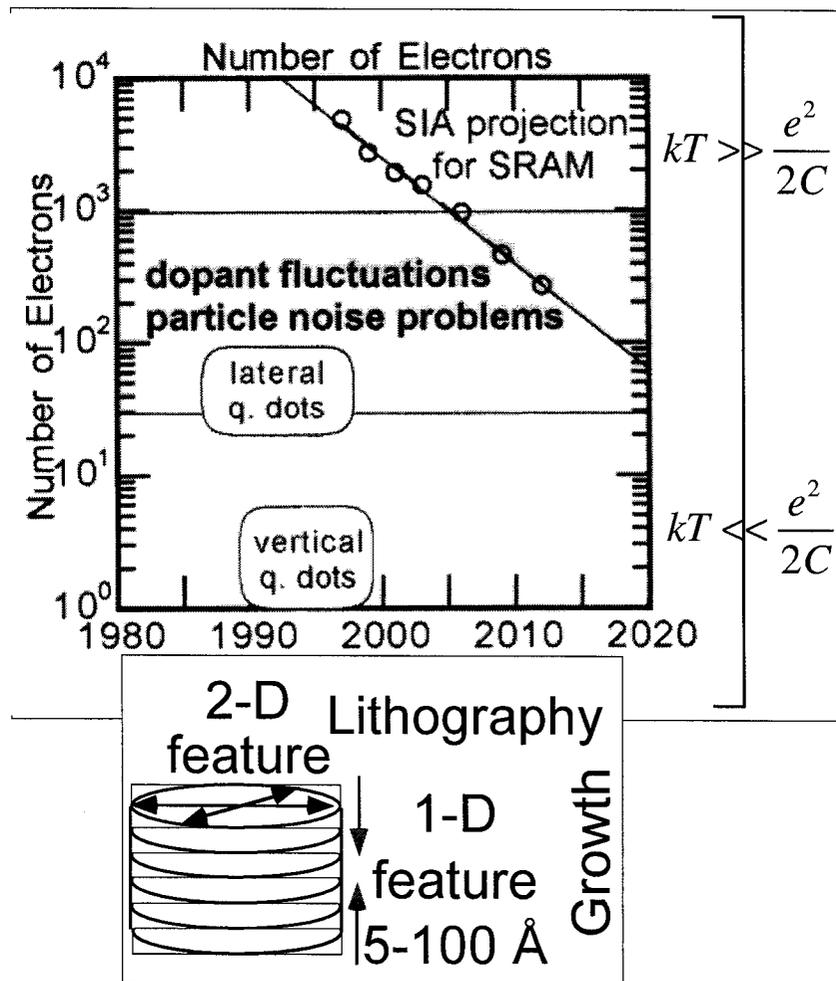
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Technology Push



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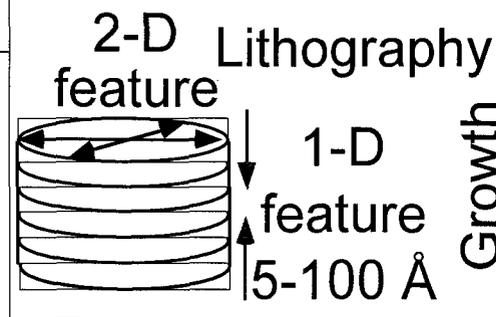
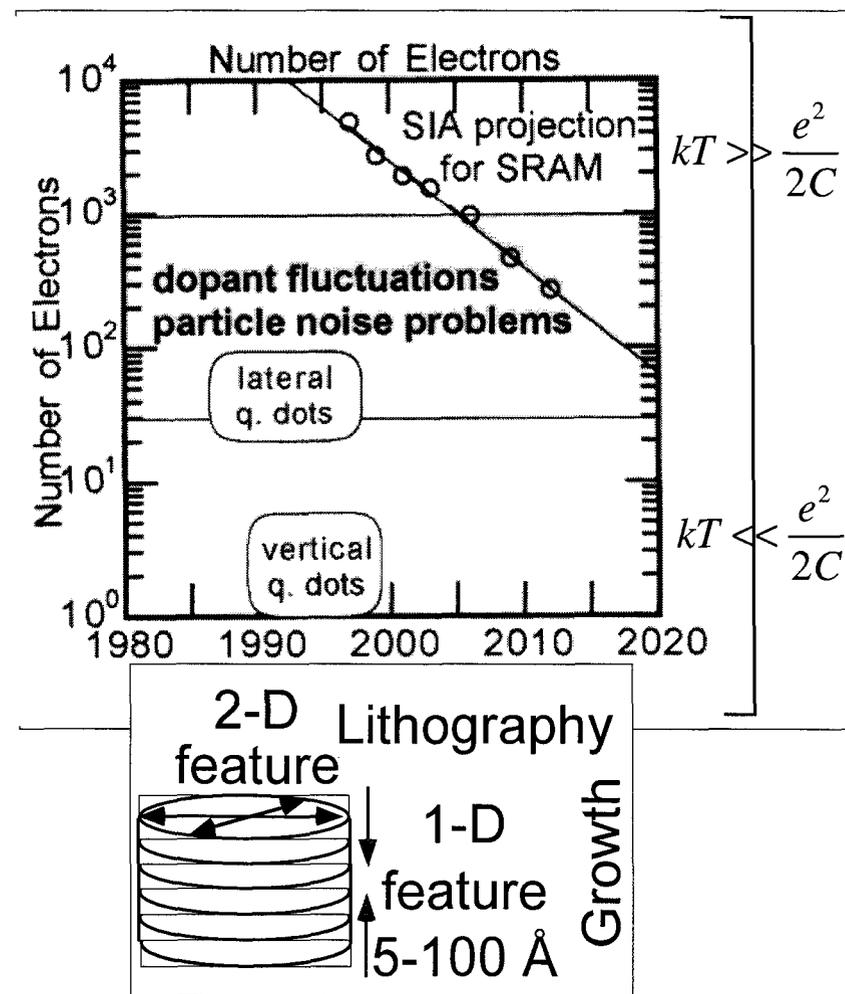
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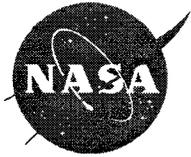
Quantum Dots Push beyond SIA with near and long term applications

- Detectors / lasers
- Memory and logic



Quantum dots go beyond the SIA roadmap and enable near and long term NASA applications





What is a Quantum Dot ?

Basic Application Mechanisms

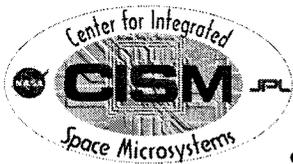
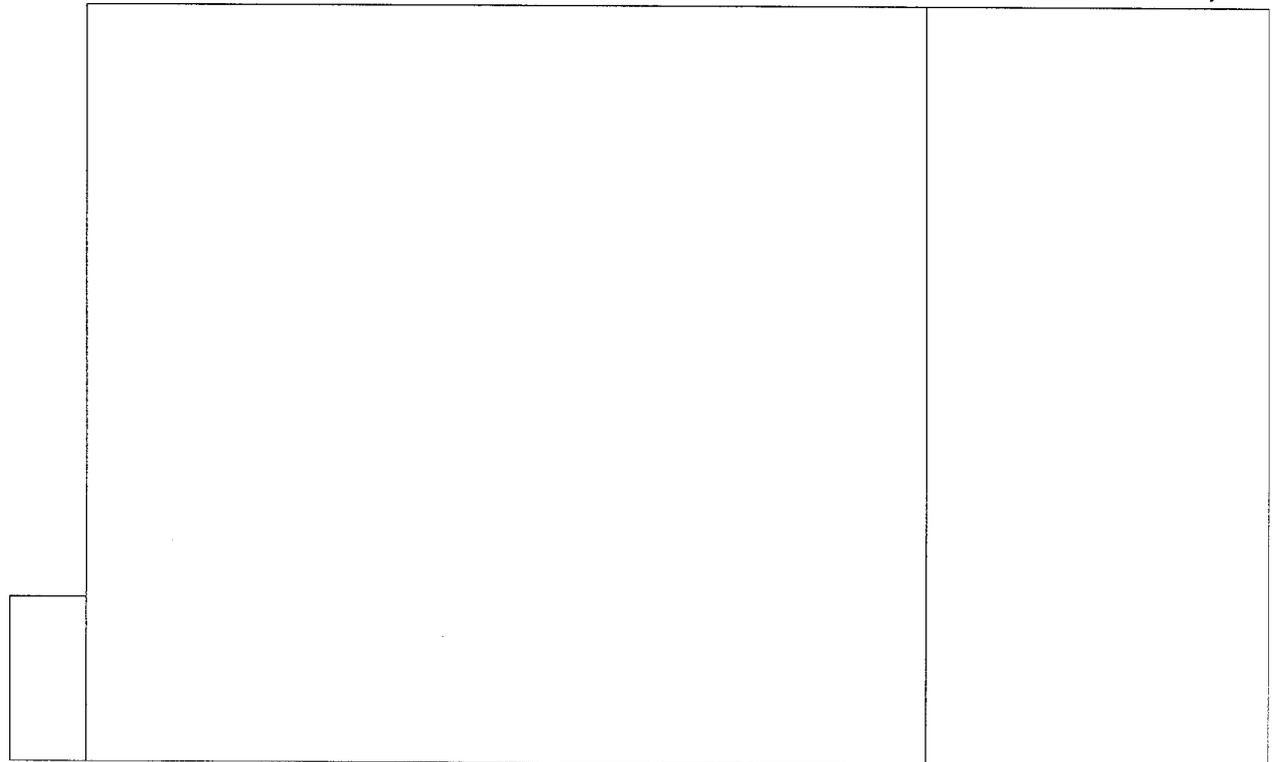


Physical Structure:

- Well conducting domain surrounded in all 3 dim. by low conducting region(s)
- Domain size on the nanometer scale

Electronic structure:

- Contains a countable number of electrons
- Electron energy may be quantized -> artificial atoms (coupled QD->molecule)





What is a Quantum Dot ?

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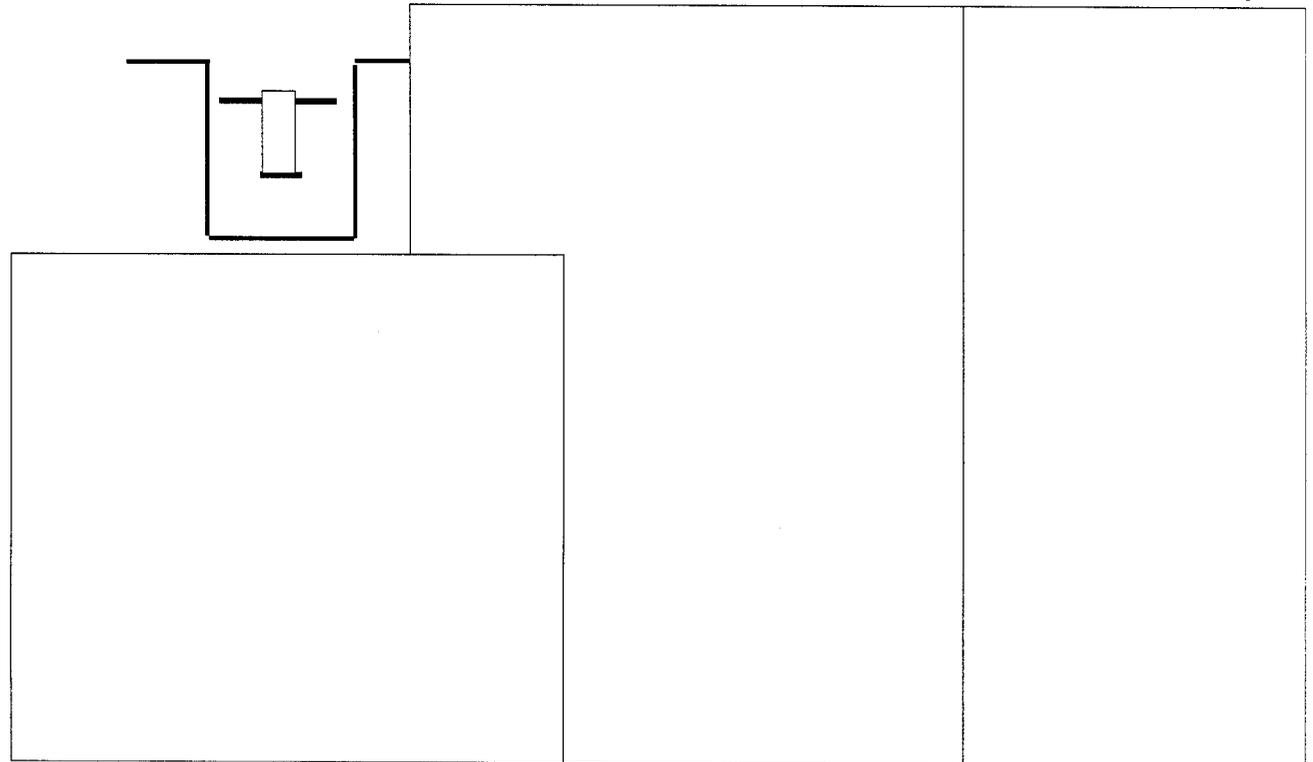


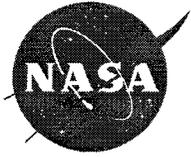
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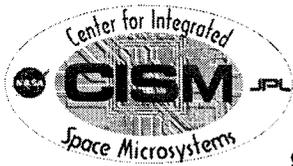
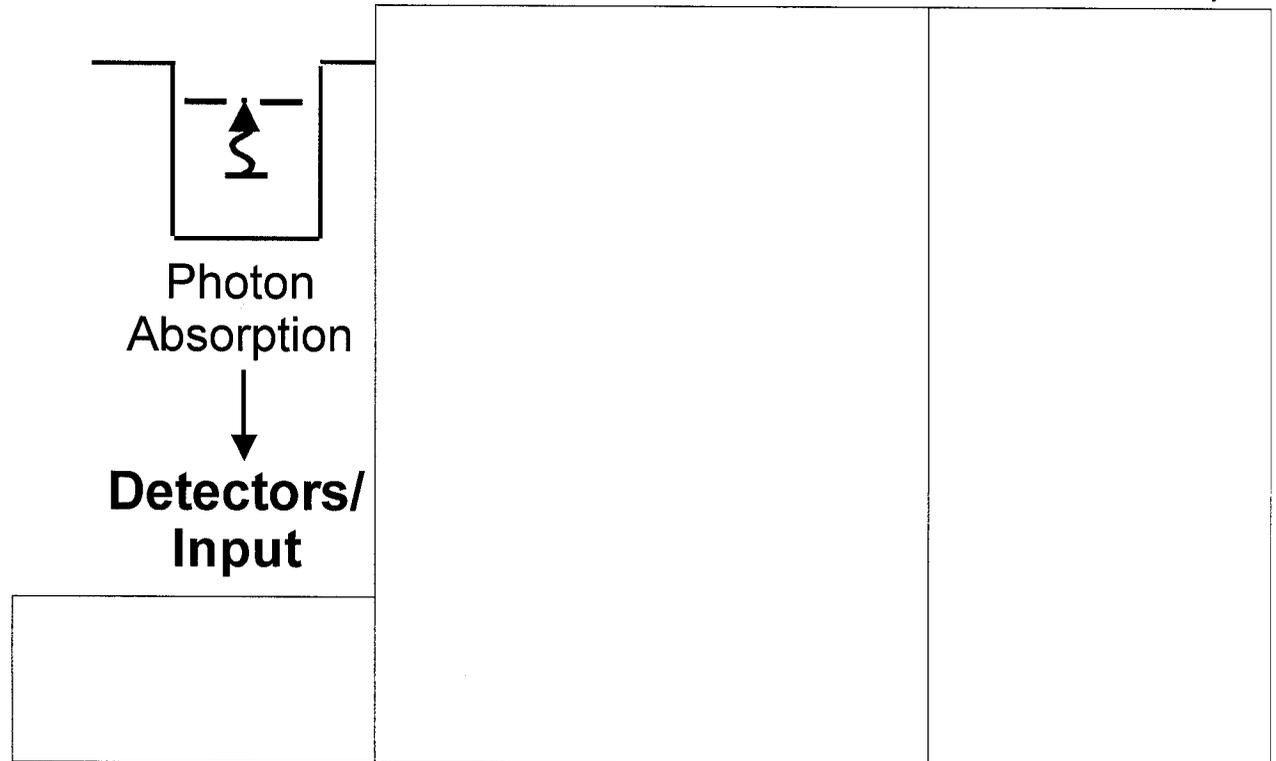


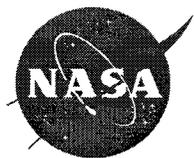
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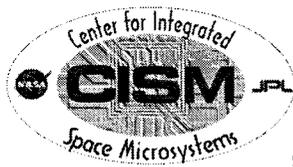
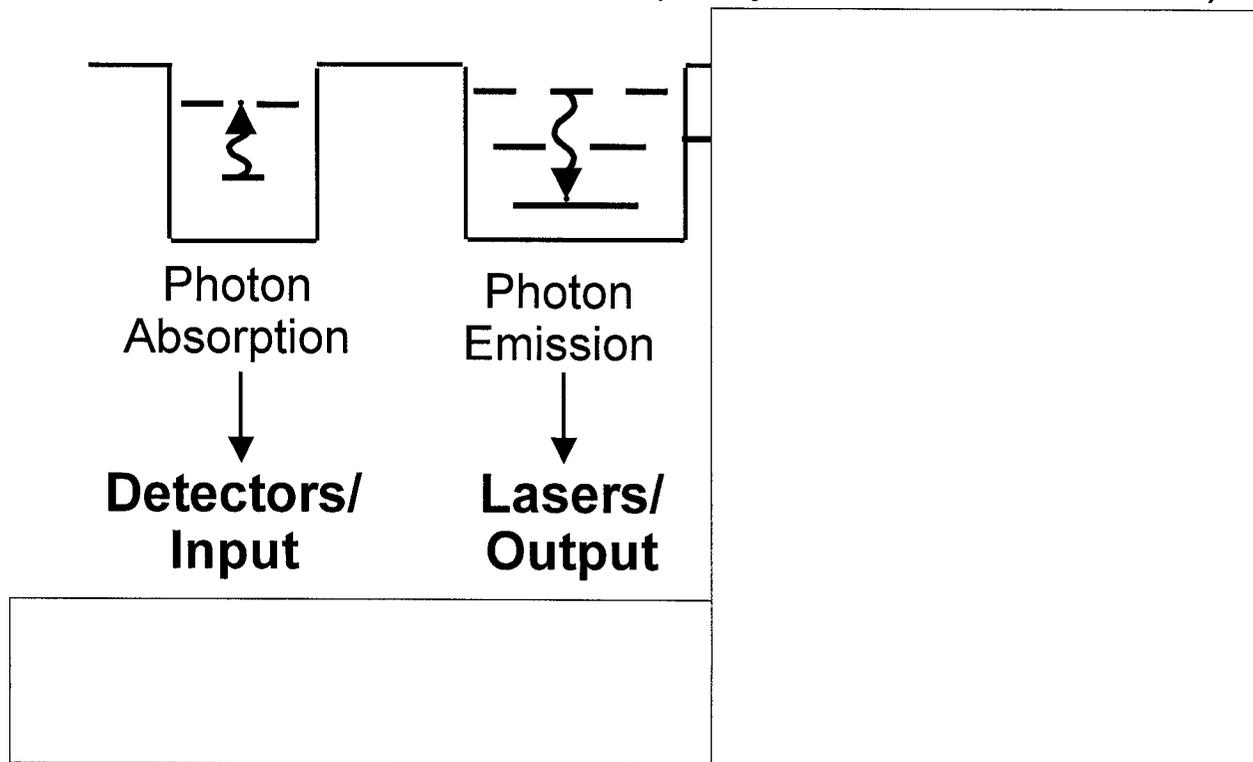


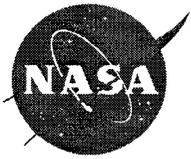
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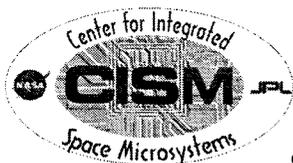
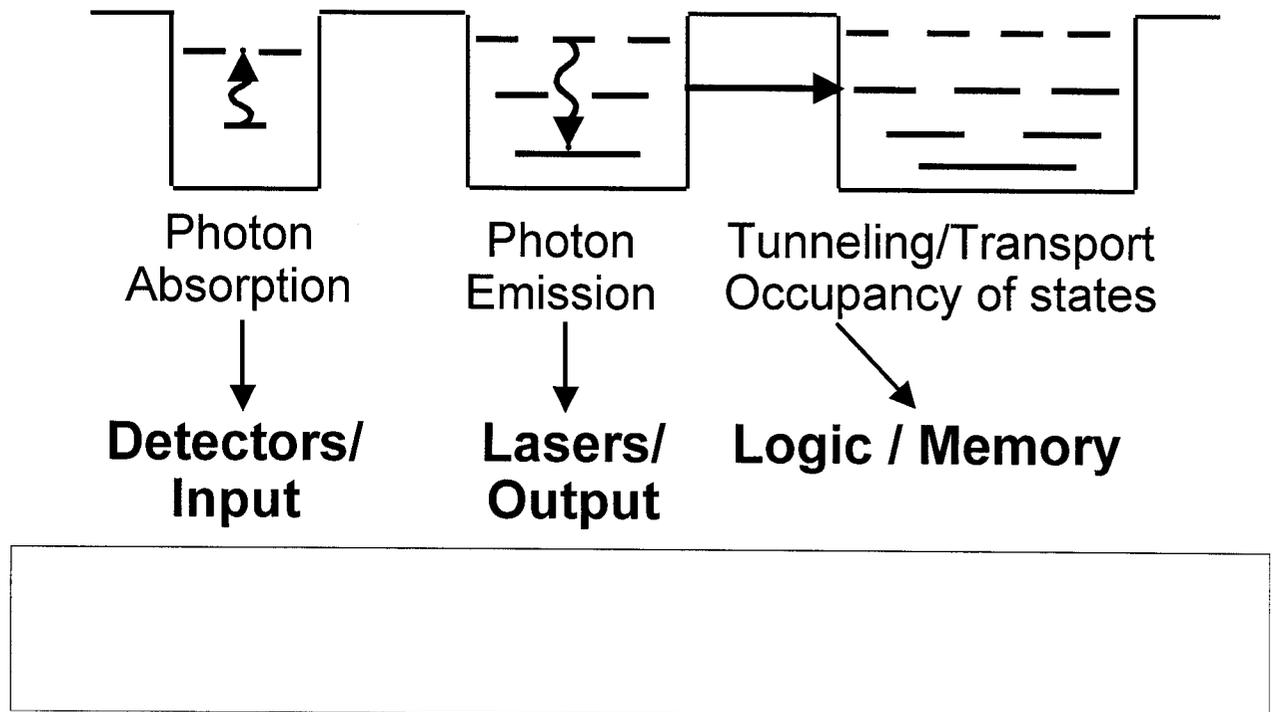


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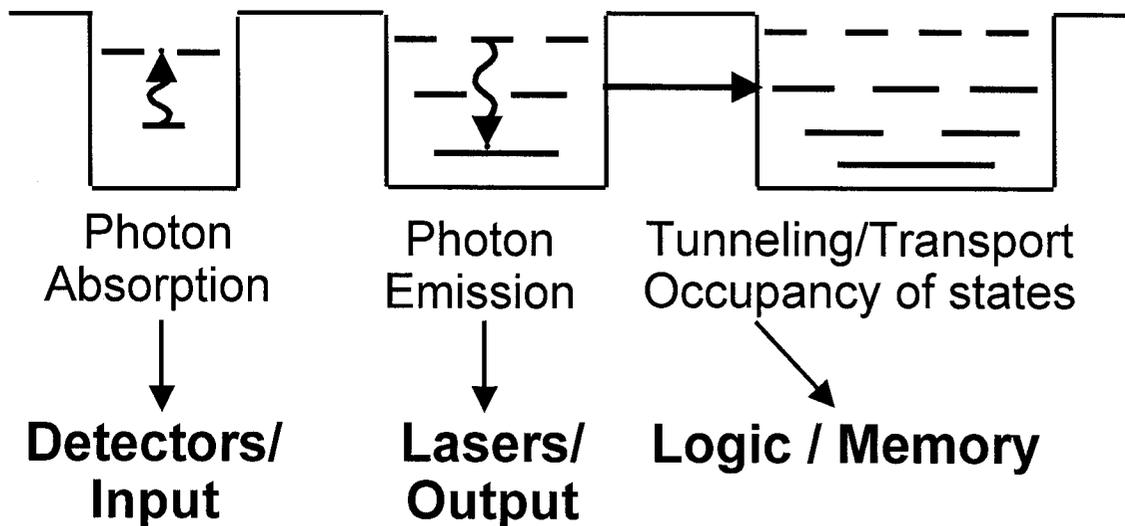
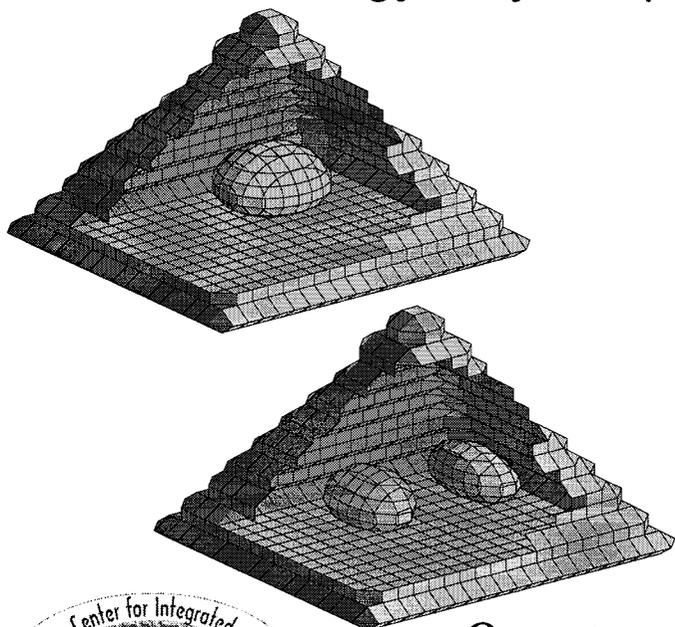


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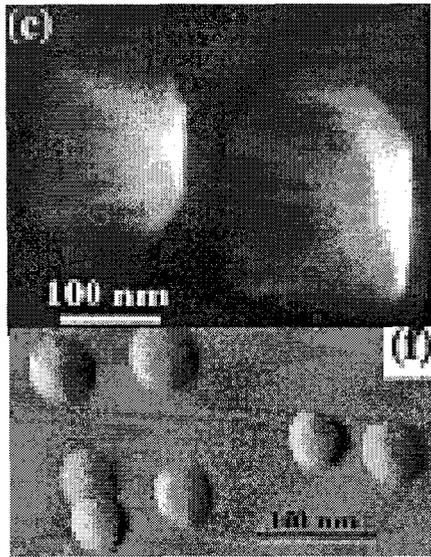


Quantum dots are artificial atoms that can be custom designed for a variety of applications





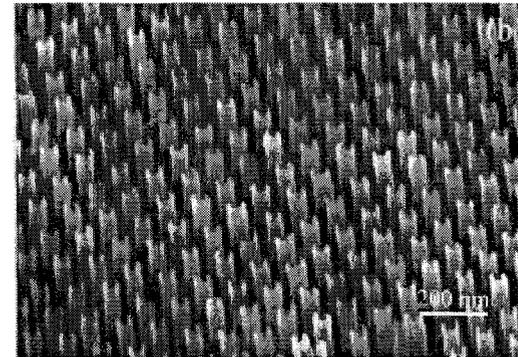
Nanotechnology / Nanoelectronic Example Implementations



**Self-assembled ,
InGaAs on GaAs.**

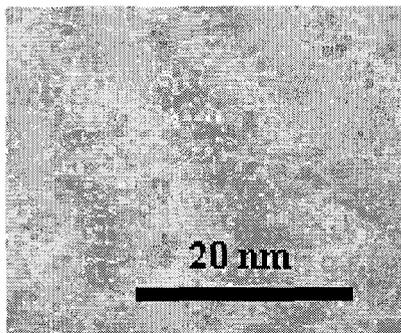
Pyramidal or
dome
shaped

R.Leon,JPL(1998)



**Nanotube
Arrays,**

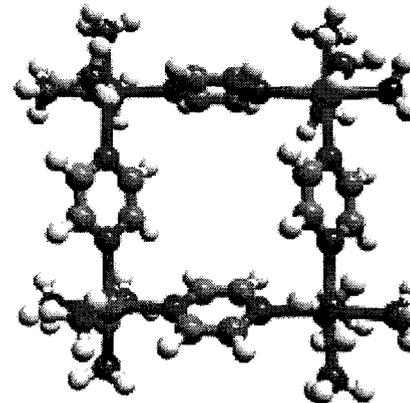
Jimmy Xu,
Brown Univ.
(1999)



Nanocrystals:

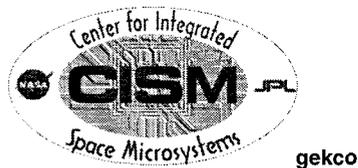
Si implanted in SiO₂

Atwater, Caltech
(1996)



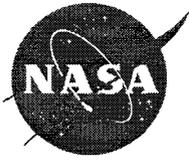
Molecular Dots

Ruthenium-based
molecule
Ru₄(NH₃)₁₆(C₄H₄
N₂)₄¹⁰⁺
proposed by Marya
Lieberman, Notre
Dame (1999)



*Low Dimensional quantum confinement
can be achieved in a variety of material systems*

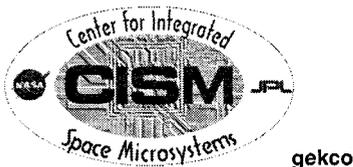




Nanotechnology Project Portfolio



- **Modeling**
 - Enable the exploration of the nanotechnology design space.
- **Characterization**
 - Optical, structural, transport and radiation testing.
- **Devices**
 - **Lasers / Output:**
Enable radiation hard, narrow linewidth tunable lasers.
 - **Sensors / Input:**
Enable acoustic and electronic sensors based on nanotubes.
 - **Memory:**
Enable high density, low power, non-volatile, radiation hard storage.
- **Architectures:**
 - Enable massively parallel and fault tolerant computing architectures.



Future deep space applications will directly benefit from directed nanotechnology research

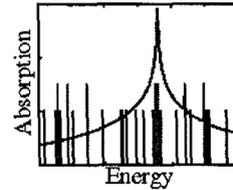
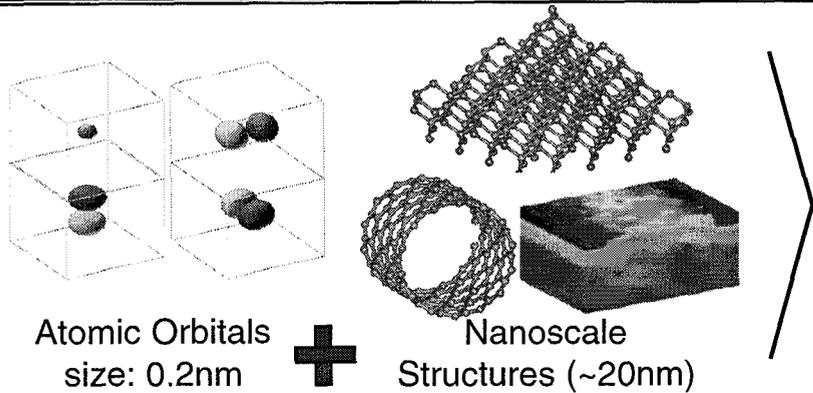




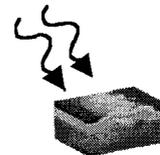
Quantum Dot Modeling - Development of Bottom-Up Nanoelectronic Modeling Tool

Nano-scale Device Analysis / Synthesis

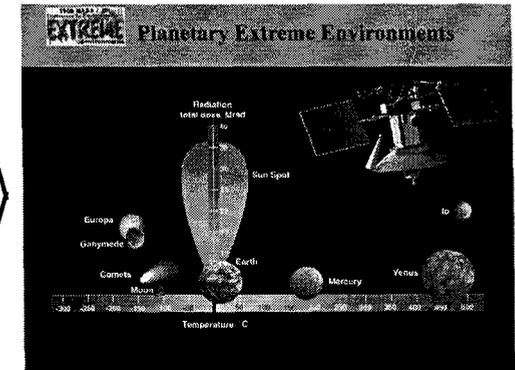
Development of a Bottom-Up Nanoelectronic Modeling Tool



New Devices for
Sensing and
Computing



Analyze Devices:
Environment
and Failures



Assertions / Problems:

- Nanoscale electronic structures are built today! The design space is huge: choice of materials, compositions, doping, size, shape
- Radiation on today's sub-micron devices modifies the electronics on a nanoscale.

Approach:

- Deliver a 3-D atomistic simulation tool
- Enable analysis of arbitrary crystal structures, particles, atom compositions and bond/structure at arbitrary temperatures and ambient electric and magnetic fields.

Collaborators:

- U. of Alabama, Ames, Purdue



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Modeling will narrow the empirical search space!

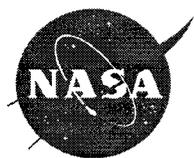
NASA Relevance:

- Enable new devices needed for NASA missions beyond existing industry roadmap:
 - Water detection -> 2-5 μ m Lasers and detectors.
 - Avionics -> High density, low power computing.
- Analyze state-of-the-art devices for non-commercial environments:
 - Europa -> Radiation and low temperature effects. Aging and failure modes.
 - Jovian system -> Magnetic field effects
 - Venus -> high temperature materials: SiGe

Impact:

- Low cost development of revolutionary technology
- Narrow empirical/experimental search space





Need for Nanoelectronic Simulation

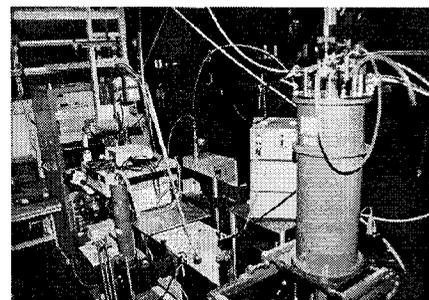
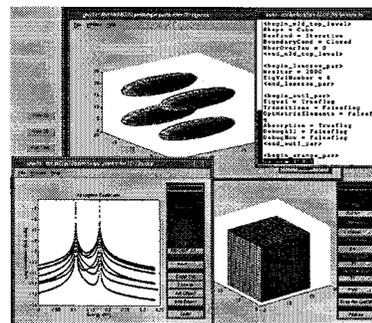
Problems:

- Design space is huge
 - Choice of materials, shapes, orientations, dopings, heat anneals
- Characterizations are incomplete and invasive / destructive

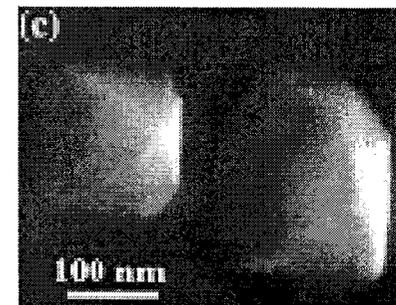
Simulation Impact:

- Aide Design
 - Fast, cost effective.
 - > Device performance already successful for 1-D quantum devices
- Aide Characterization
 - Non-invasive
 - More accurate
 - > Structure and doping analysis already successful for 1-D quantum devices

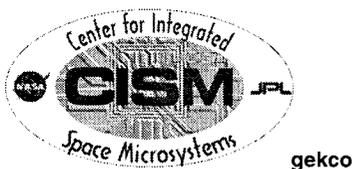
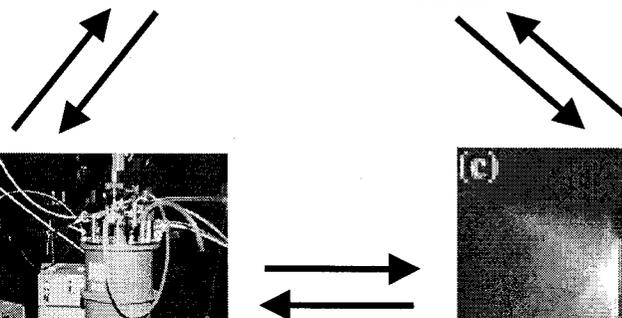
Simulation



Characterization



Fabrication



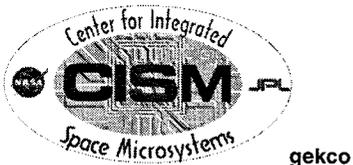
Modeling, Characterization and Fabrication are inseparable for nanoscale devices





Objective

- **Long term objective:**
 - Develop and demonstrate a physics-based, atomistic simulation tool for semiconductor quantum dots and molecular based electronic devices
- **Near term objective:**
 - Develop this year the technology necessary to simulate optical transitions in a single quantum dot
- **Tasks in FY 00:**
 - Alloyed dot simulation (04/00)
 - Shared memory parallelization (05/00)
 - 3-D visualization (05/00)
 - Atomistic grading simulation (07/00)
 - Atomistic impurity simulation (09/00)



*We build a bottom-up, atomistic
nanoelectronic design tool*





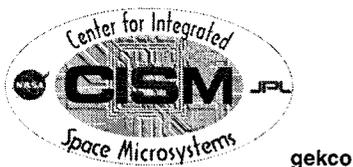
Related Work

Investigator	Location	Hamiltonian	Atomistic	Many-Body	Extendable to Molecules?
Pryor	Lund	$k \cdot p$	NO	YES	NO
Bimberg	Berlin	$k \cdot p$	NO	NO	NO
Freund	Brown	$k \cdot p$	NO	NO	NO
Leburton	Illinois	1 Band	NO	NO	NO
Zunger	NREL	Pseudopotential	YES	NO	NO
Bowen/Klimeck	JPL	Tight-binding	YES	NO*	YES

* - Planned for 01

Why JPL? JPL has expertise and infrastructure to tackle such large problems.

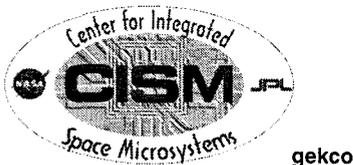
We are in a excellent position to simulate molecular electronics from the bottom -up





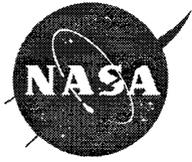
Technical Accomplishments (Physics)

- **Genetic algorithm based material parameter analysis**
 - Establish a material basis set needed for atomistic simulations
- **Mechanical strain calculation**
 - Enable proper modeling of optical bandgaps
 - > proper tuning of optical transitions
- **Alloyed Dot simulation**
 - Enable simulation of realistic quantum dot compositions
 - Enable analysis of inhomogeneous linewidth broadening due to alloy disorder
- **Atomistic grading simulation**
 - Enable simulation of realistic quantum dot interfaces
 - Enable simulation of interface interdiffusion and the resulting modification of the confined quantum states.



*We are just starting to explore
the capabilities of this simulator!*

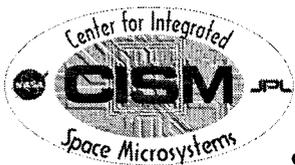




Technical Accomplishments (Software)

- **Parallelization**
 - Evaluate performance of 2 different parallel computing paradigms:
 - shared memory (all CPUs can access the same memory)
 - distributed memory (message passing between CPUs)
 - => performed a 2 million atom simulation in the distributed model
- **Analysis of general molecular inputs -> Nanotubes**
 - Enable electronic simulation of “arbitrary” crystal structures generated from other structural simulators.
 - > Expansion to Moletronics
- **Graphical User Interface Prototype**
 - Enable device, material and computer specific input to and output from a supercomputer based simulator.
- **3D Data Visualization**
 - Enable visualization of simulation results

*3 person years of software work at JPL and 22 person years
NEMO leverage enabled the simulation capabilities.*

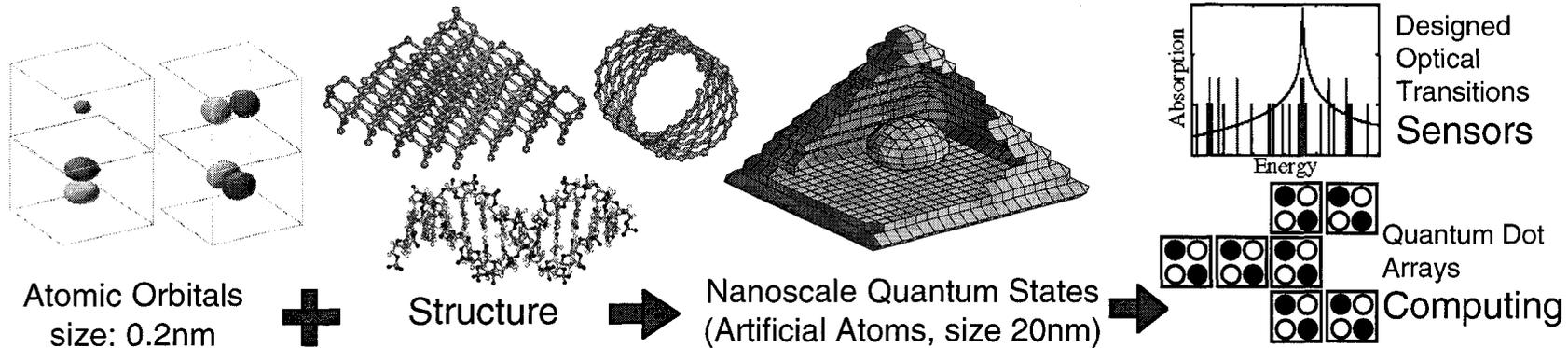


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Technical Approach



Problem:

Nanoscale device simulation requirements:

- Cannot use bulk / jellium descriptions, need description of the material atom by atom => use pseudo-potential or local orbitals
- Consider finite extend, not infinitely periodic => local orbital approach
- Need to include about one million atoms. => need massively parallel computers
- The design space is huge: choice of materials, compositions, doping, size, shape. => need a design tool

Approach:

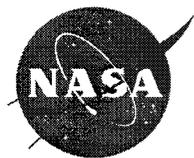
- Use local orbital description for individual atoms in arbitrary crystal / bonding configuration
 - Use s, p, and d orbitals depending on the material.
 - Use genetic algorithm to determine material parameter fitting
- Compute mechanical strain in the system.
- Develop efficient parallel algorithms to generate eigenvalues/vectors of very large matrices (N=40million for a 2 million atom system).
- Develop prototype for a graphical user interface based nanoelectronic modeling tool (NEMO-3D)

Realistic material description at the atomic level enables simulation of realistic nanoelectronic devices.

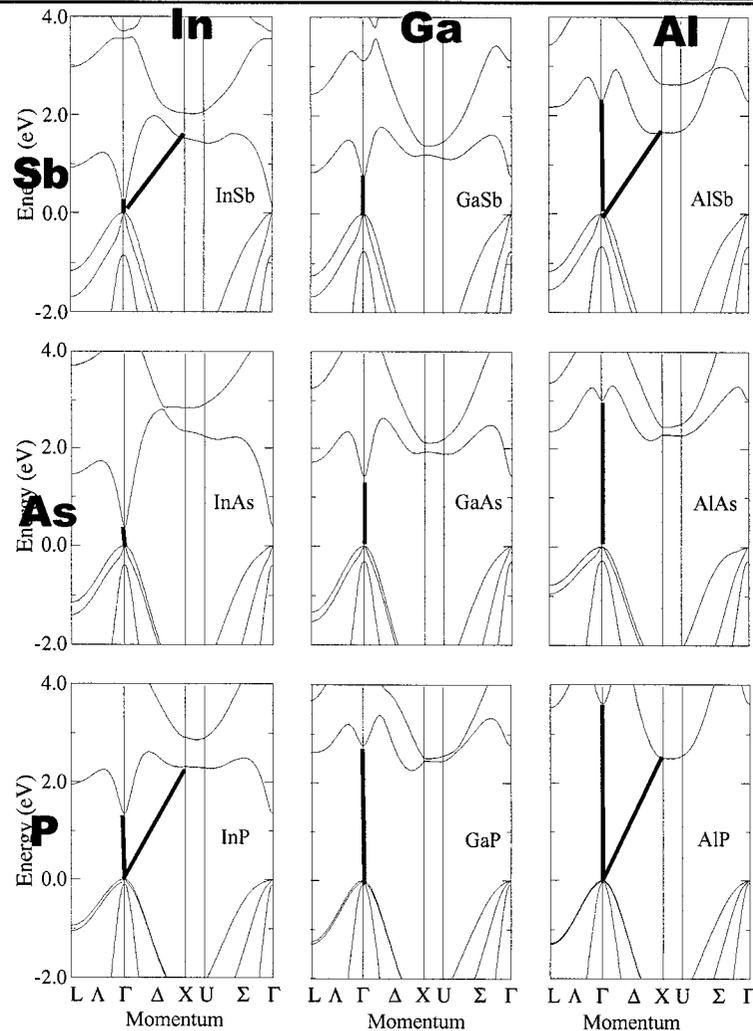


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Genetic algorithm based material parameter analysis



Problem:

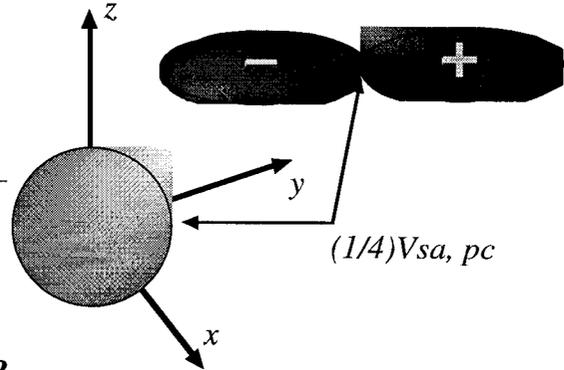
- Want atomistic / orbital based material description.
- Need to fit 15-30 orbital interaction energies to 20-30 material properties (bandgaps and masses)

Approach:

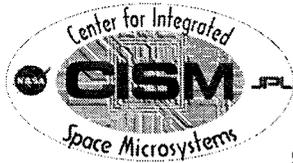
- Use massively parallel genetic algorithm to perform multidimensional optimization

Results/Impact:

- Established a 3x3 array of materials and their parameters that are the building blocks of quantum dots.
- Enable the atomistic simulation of quantum dots.

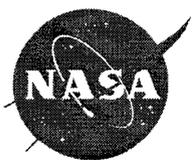


Genetic algorithm enabled the establishment of a material basis set.



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Mechanical Strain Calculations

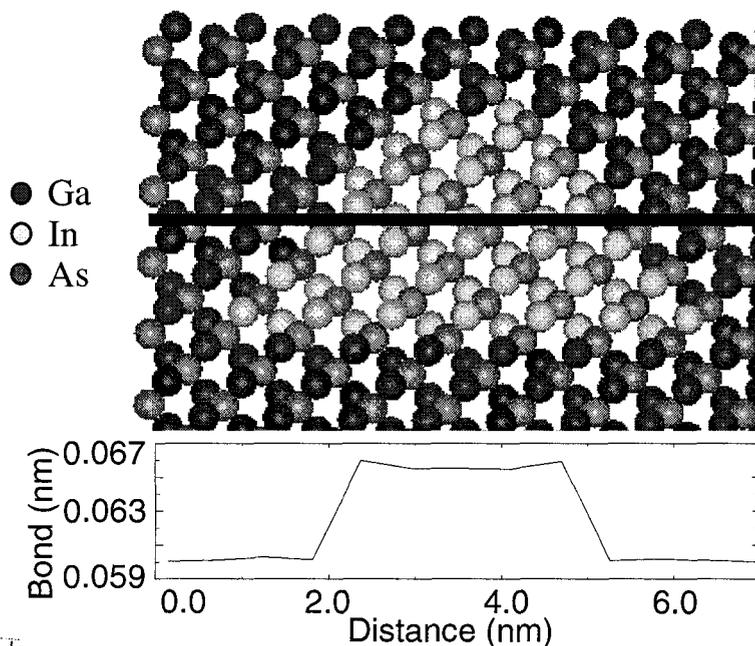
Problem:

- Self-assembly dot formation due to strain
- Small mechanical strain (5% bond length)
-> dramatic effects on electronic structures

Approach:

- Nanomechanical strain calculation
- Nanoelectronic strain calculation.

Mechanics Problem: Minimize elastic strain (Keating)



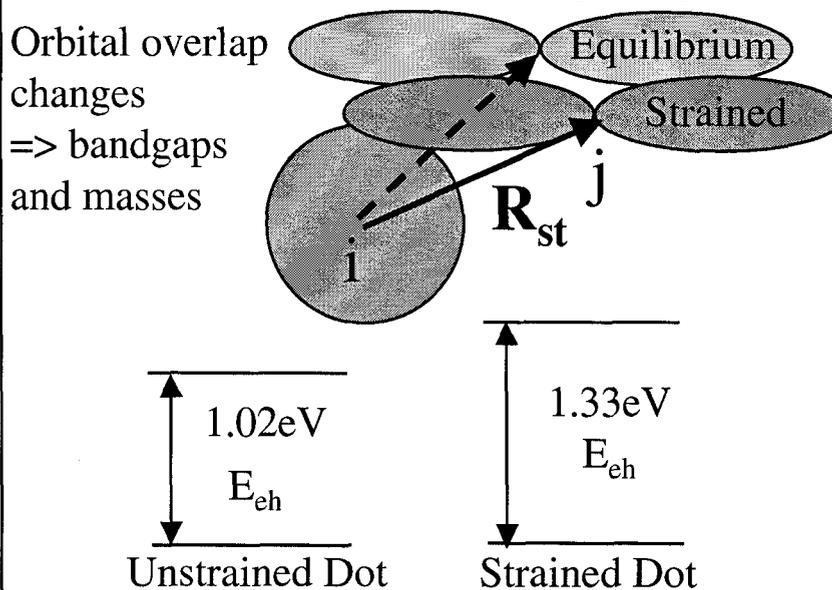
Results:

- Implemented a mechanical strain model.
- Implemented atomistic bandstructure model that comprehends strain.

Impact:

- Can simulate realistic quantum dots.
- Can estimate optical transition energies properly.

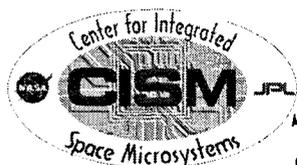
Electronics Problem: Effect of overlap changes



Pyramidal InAs Dot Simulation

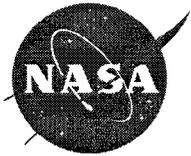
Base: 7nm x 7nm Height: 3nm Embedded in GaAs

Small strain has dramatic effects on the electronic structure.



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Alloy Disorder in Quantum Dots

Problem:

- Cations are randomly distributed in alloy dots.
- Does alloy disorder limit electronic structure uniformity for dot ensembles?

Approach:

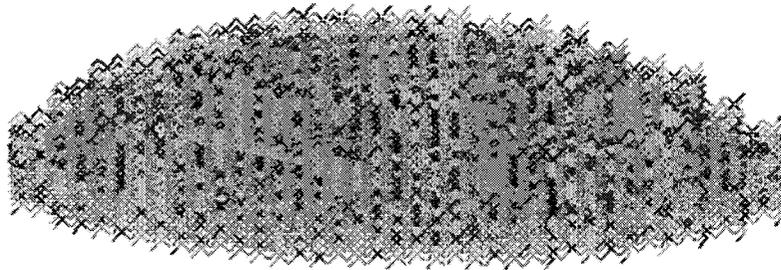
- Simulate a statistical ensemble of alloyed dots.
- Requires atomistic simulation tool.

Results:

- Simulated 50 dots with random cation distributions.
- Inhomogeneous broadening factor of 9.4meV due to alloy disorder.

Impact:

- Fundamental uniformity limit for ensemble of alloy-based quantum dots.

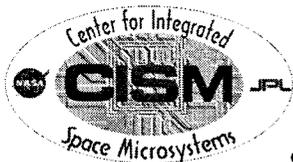
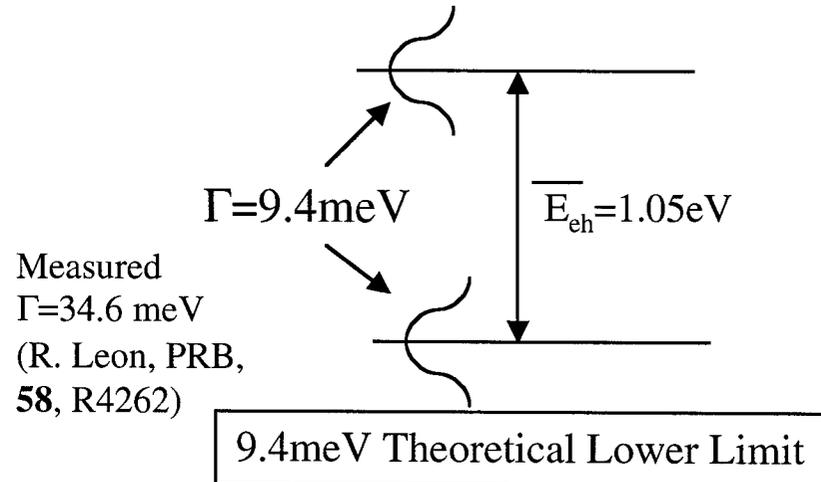


In_{0.6}Ga_{0.4}As Lense Shaped Dot

(Diameter=30nm, Height=5nm, GaAs embedded)

In and Ga atoms are randomly distributed
Inhomogeneous Broadening?

Simulation of Alloy Dot Ensemble



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Alloy disorder presents a theoretical lower limit on optical linewidths





Atomistic Grading Simulation

Problem:

- Quantum dot interfaces may not be sharp.
- There may be cation redistribution around the interface => grading of the concentration.
- How does the interfacial grading affect the electronic structure?

Approach:

- Simulate quantum dot atomistically with graded interfaces as a function of interdiffusion length.

Results:

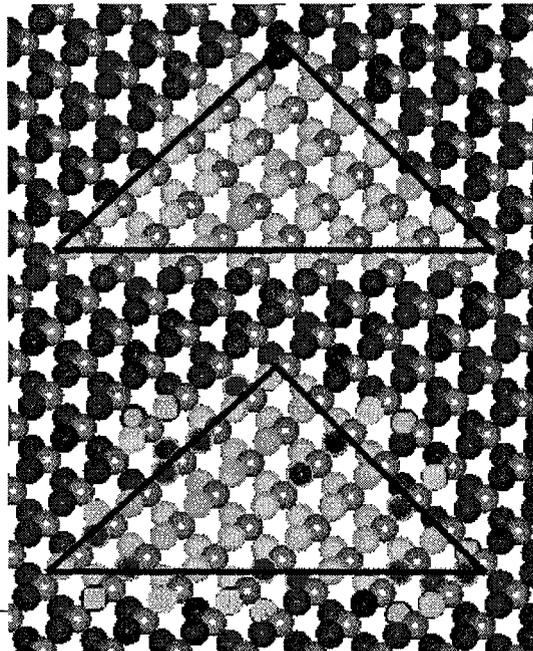
- More Ga in the quantum dot raises the energy of the transition energies.
- Less Ga in the barriers softens the barriers, reduces the binding of the excited states to the quantum dot and reduces $\Delta E = E_2 - E_1$.

Impact:

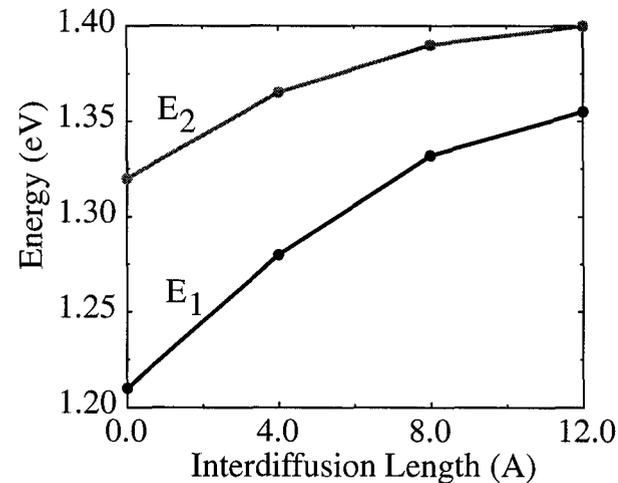
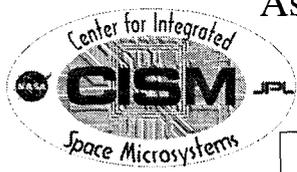
- Verify experimentally suggested interdiffusion process may be responsible for blue shift and reduction in ΔE .

Cartoon Visualization of Interdiffusion

Slice through 2 Qdots with thickness of 3 atoms - with and without interdiffusion



- Ga
- In
- As



Pyramidal InAs in GaAs, Diameter=10nm, Height=4.2nm
5 samples per data point

Interdiffusion widens the bandgap

=> blueshift





Code Parallelization

Problem:

- Need to calculate eigenvalues of a complex matrix of the order of 40 million.
=> must parallelize code

Approach:

- Evaluate 2 parallel programming paradigms
 - Shared memory (OpenMP) - CPUs can access the same memory.
 - Distributed memory - CPUs exchange data through messages (MPI) - data synchronization performed explicitly by program.

Vision:

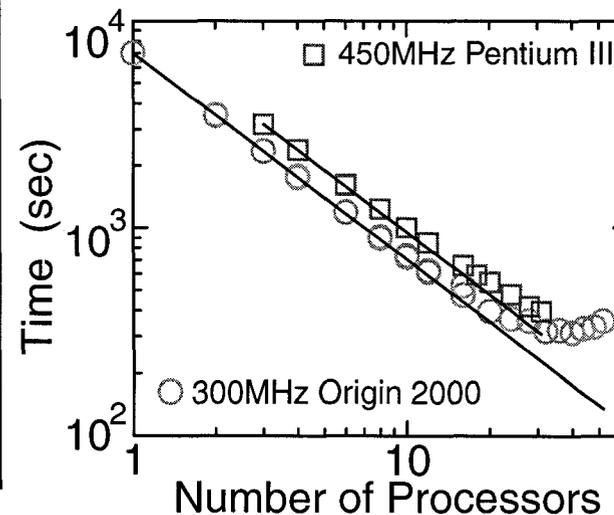
- Utilize a designated beowulf cluster of PC's as a workhorse for these simulations. Each node might have 1-4 shared memory CPUs on one motherboard.
- Envision a "mixed" code with outer level MPI parallelism and inner level OpenMP parallelism.
 - This will run on a commercial supercomputer like an SGI Origin 2000 as well as a beowulf.

Results:

- Inner level OpenMP parallelism does not speed up code significantly. Dynamic creation and destruction of threads is too expensive.
- Decided to abandon the OpenMP implementation and concentrate on the optimization and scaling of the MPI version.

Impact:

- Enabled simulation of 2 million atom systems with 20 orbitals on each atom
=> matrix of order 40million



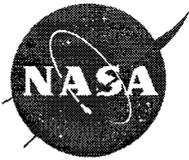
Compare
Origin 2000
vs.
Beowulf:

10 Lanczos
Iterations for a
1million atom
system.



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Cluster of commodity PC's can beat a supercomputer for our problem

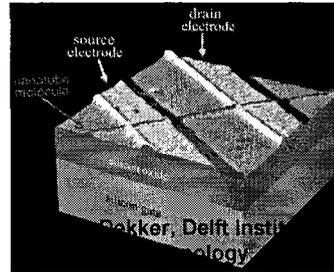


Incorporate Arbitrary Molecular Files -> Nanotubes



Background:

- Carbon Nanotubes are currently explored for electronic and structural applications.



Objective/Motivation:

- Simulate optical interactions and electron transport in nanotubes

Problem:

- Need nanotube structural information.
- We do not have that expertise.

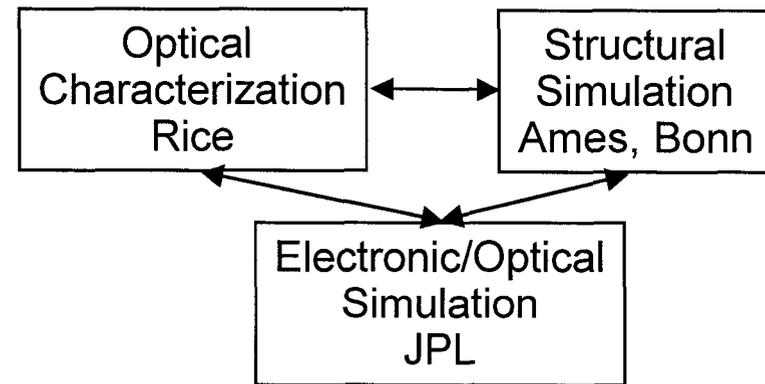
Approach:

- Expanded code to read standard chemical structure file format.
- Get structural information from other researchers.

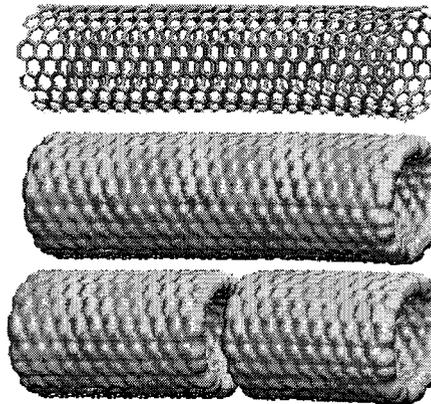
Result:

- Simulated nanotube ground states and density of states.

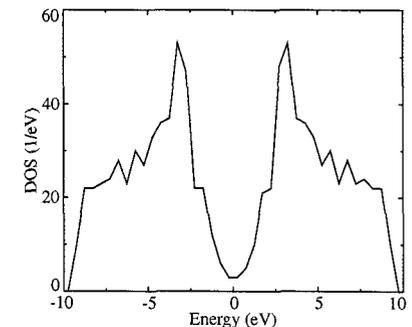
Possible Cooperation from Nanospace 2000 Conference:



Preliminary Data



Finite size nanotube ground and excited state



Density of States



We can input molecular dynamics based files and perform electronic structure calculations





Software Structure Prototype/Vision



Objective:

- Design, develop, test and deliver an interactive quantum dev. design tool
- Customers: Experimentalists not Simulation Specialists !

Problem:

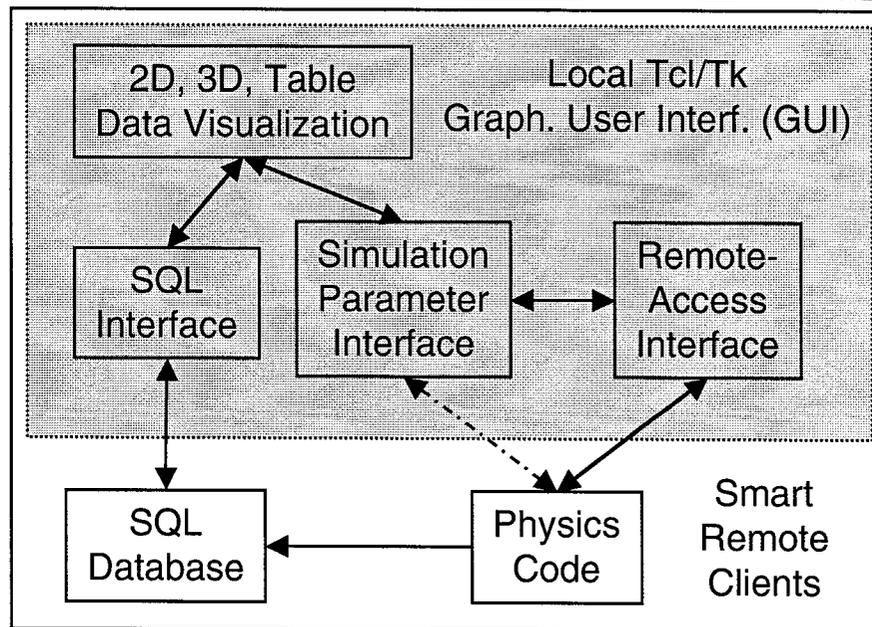
- Simulations are CPU intensive -> need supercomputers
- Datasets are typically 4-dim -> need custom visualization
- Local workstations are PC, MAC, SUN or SGI -> need portable Graph. User Interf.
- Input requirements change fast -> need dynamic GUI design

Approach:

- Heterogeneous client-server Tcl/Tk-based GUI

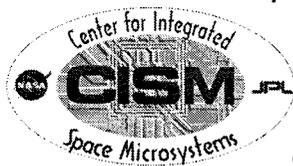
Impact:

- Using this approach on 2 completely independent simulators with little additional development time.



Smarts are OUTSIDE the GUI:

- Physics code contains I/O structures
- Database completely general
- > GUI retrieves I/O structures and data from smart clients.
- > Flexibility for user and developer



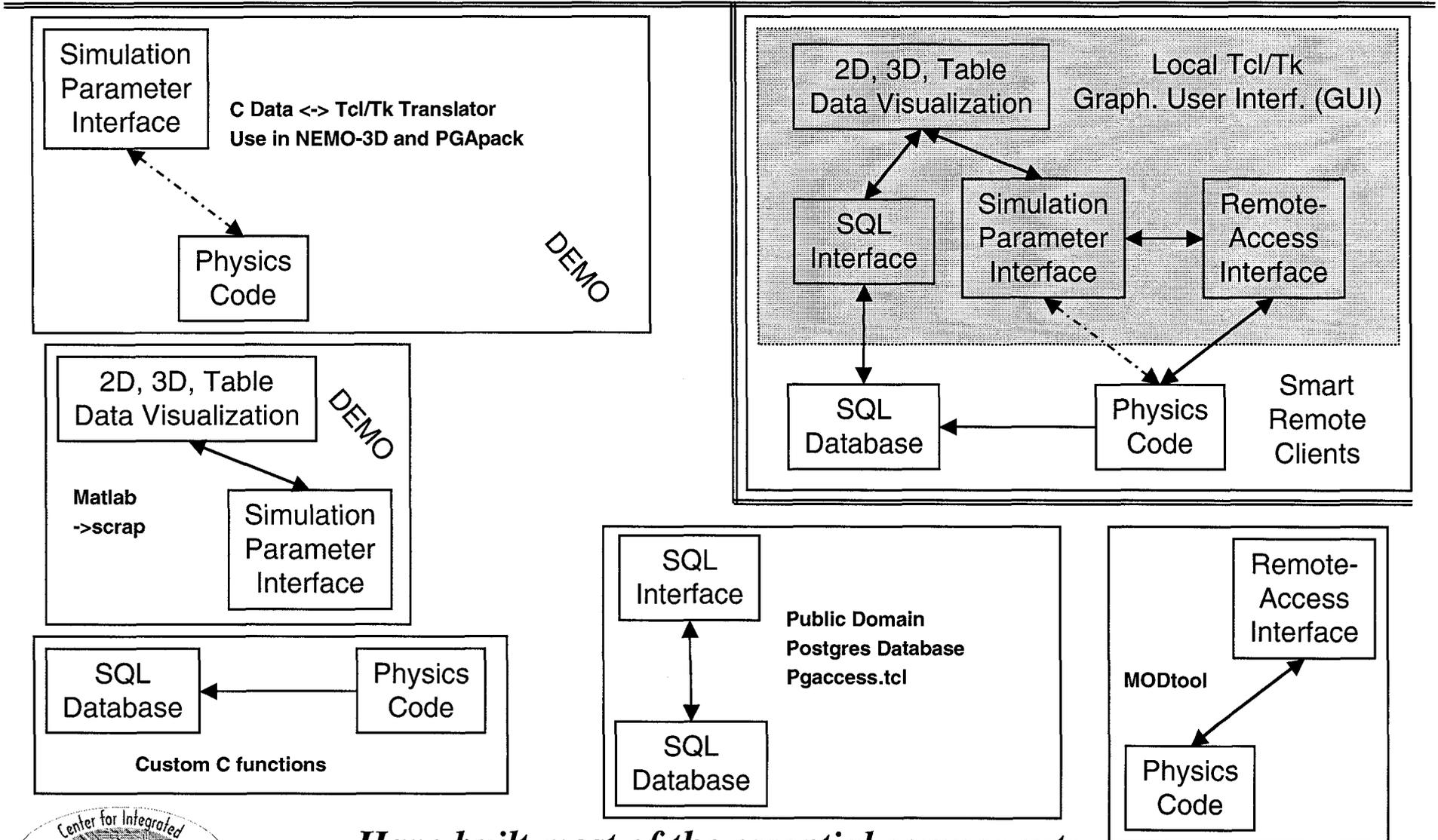
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Flexible software design enables use in various different simulators

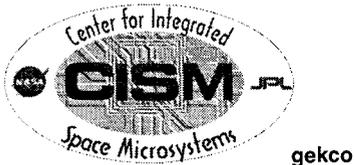




Software Structure Status



Have built most of the essential components, need to go through integration process.





Plans

Plans for FY 01:

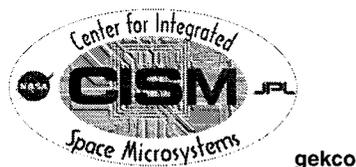
- Simulation of ensembles of alloyed quantum dots
 - Study fundamental limit of spectral lines due to alloy disorder
- Simulation of many-body effects via configuration interaction
 - Simulate optical transitions including effects of excitons
- Electron transport through quantum dot
 - Explore design possibilities for electronic transport devices

Plans for FY 02:

- Transport through Nanotubes, DNA including bond deformation effects

Plans for outgoing years:

- Develop a world-class 3-d nanoelectronic modeling tool

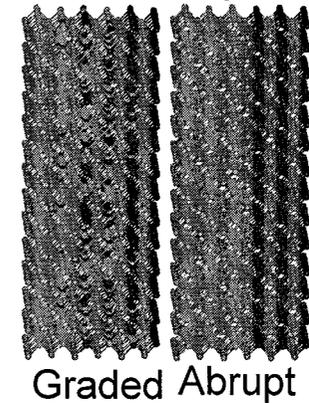
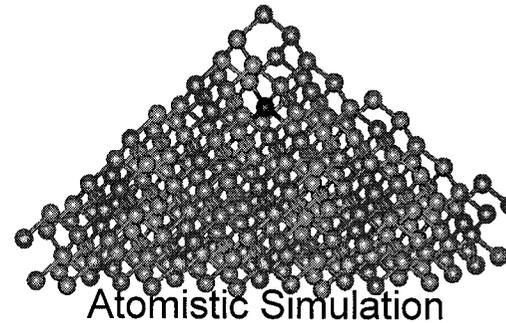




Conclusions / Future Vision

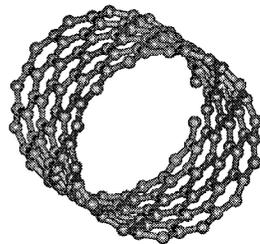
- Parallelization (2 million atoms), visualization
- Graded junctions, alloy disorder, strain
- Made significant progress towards a general atomistic simulation tool
- Envision this tool to have impact on quantum dots, end of SIA roadmap issues, and molelectronics.

Quantum Dots Grading

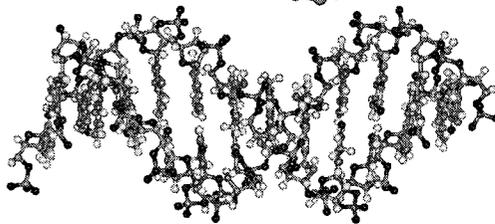


Transport in Molecules

Carbon Nanotubes

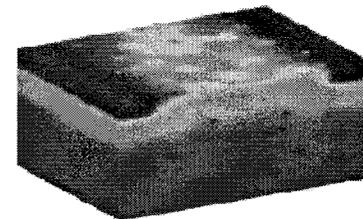


DNA

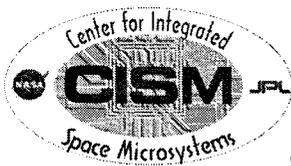
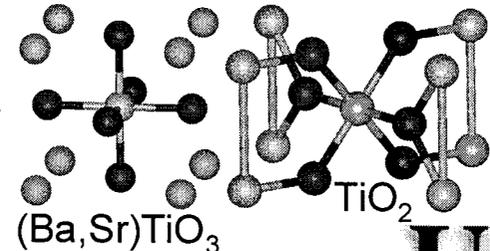


End of SIA Roadmap

Dopant Fluctuations in Ultra-scaled CMOS



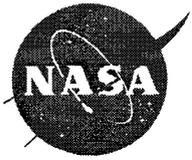
Electron Transport in Exotic Dielectrics



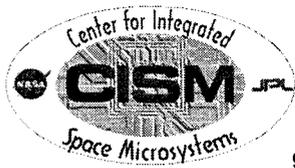
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The best is still to come!



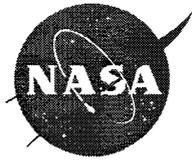


Backup Foils



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Quantum Dot Modeling - Development of Bottom-Up Nanoelectronic Modeling Tool

Quantum Dots: Optical and Structural characterization



Task Lead: Rosa Leon

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Objectives:

COMPUTERS

- Quantum Dots can enable new types of computing architectures (for example QCA).

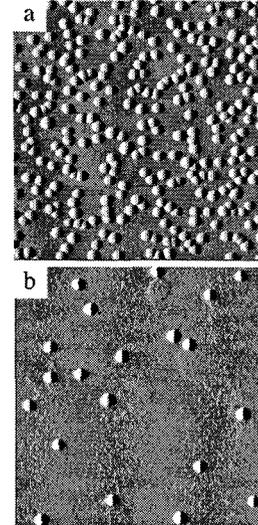
MEMORIES

- QDs can be used in ultra-high density optical memories.

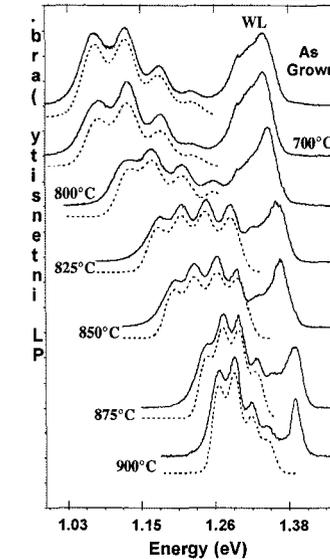
RADIATION TOLERANCE

- QDs enable radiation-hard opto-electronic devices.

InGaAs Quantum Dots



Squares are 1 μm by 1 μm



Tuning inter-sublevel energies in Quantum Dots

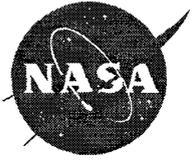
Approach:

- Achieve positional order of Quantum Dots (QDs) by combining patterning and various types of growth experiments.
- Implement experimental capabilities for in-house QD characterization.
- Collaborate with Universities on fabrication, growth experiments, and characterization.
- Perform tests and experiments on existing QD structures - understand QD properties and how they impact their various device applications.



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Quantum Dot Fabrication for Lasers

Task Lead: Yueming Qiu

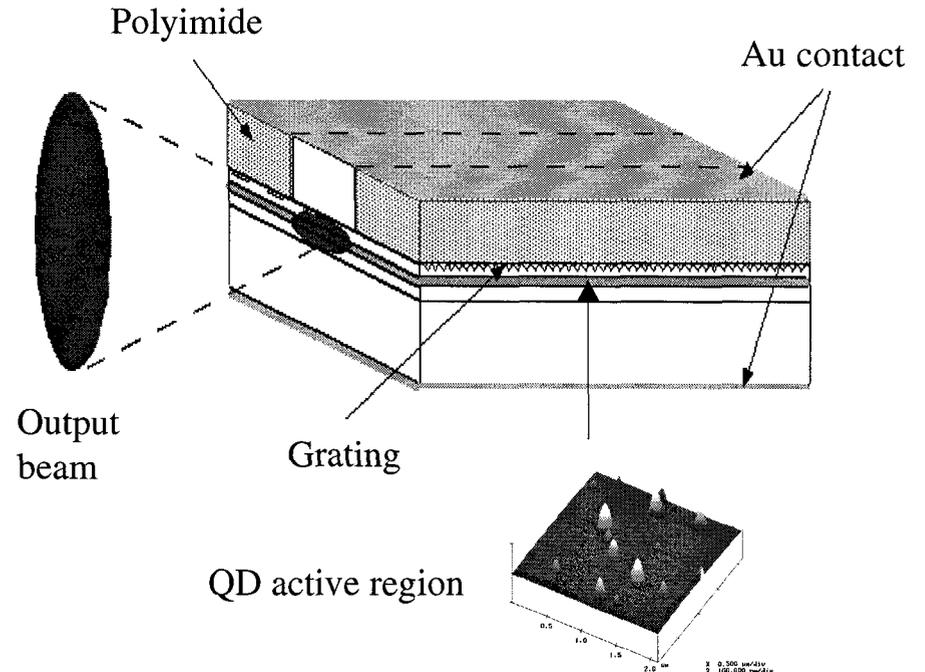


Objective:

- Design and fabricate high efficient, low power consumption, radiation hard QD based optoelectronic devices, such as:
 - lasers
 - ultralow threshold current density
 - temperature insensitive
 - narrow linewidth

NASA applications:

- Large format, low noise IR detector arrays are enabling technology for SSE
- Broad area of applicability:
 - Spectroscopy
 - Microinstruments
 - Communications
 - LIDAR and Interferometry



Collaborators:

- University of New Mexico



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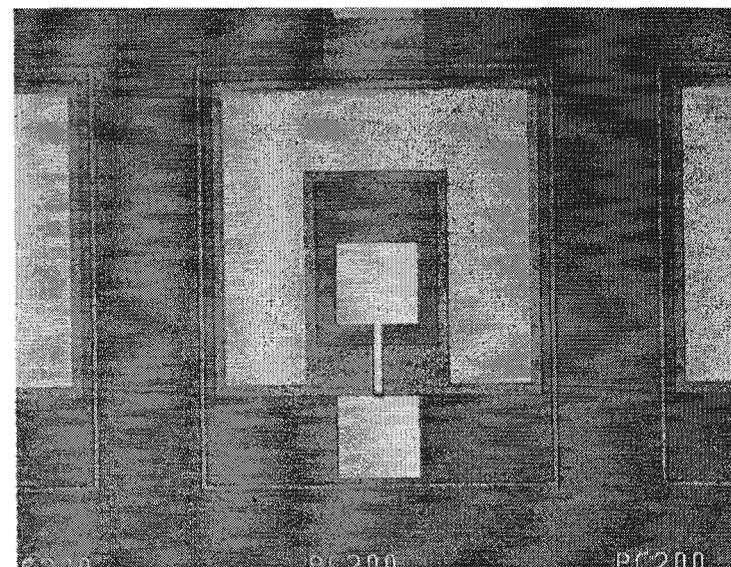
Single Electron Nonvolatile Memory

Task Lead: Doug Bell



Task Purpose/Objectives:

- Develop a *room-temperature, radiation-tolerant* memory technology based on single-electron storage.
- Decrease read/write time by orders of magnitude using a novel peaked-tunnel-barrier concept.
- Increase capability for computing storage by increasing storage density and decreasing storage power.



Major Products:

- Silicon nanocrystal floating-gate memory
- Shape-engineered tunnel barrier for breakthrough read/write speed.

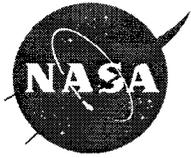
NASA Relevance:

- **Space Science:** (autonomous spacecraft systems and robots)
- **Earth Science:** (autonomous navigation / guidance; sensing and sensor webs)
- **Human Exploration:** (autonomous robotic monitoring systems)



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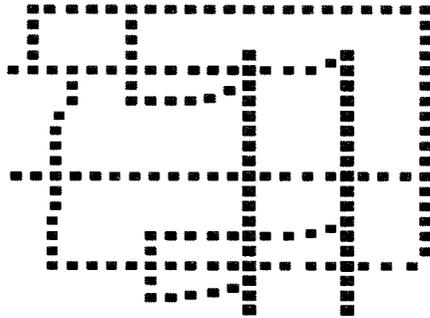




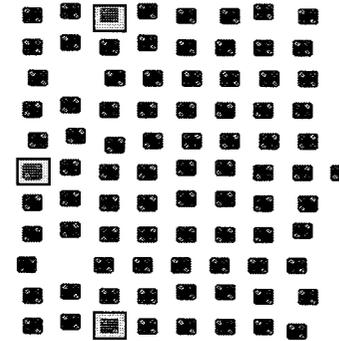
Quantum Dots Based Computing:

Quantum Dots Cellular Automata (QCA) Architectures and Applications

Task Lead: Amir Fijani



Novel QCA Circuits: A Bit-Serial Adder



Novel QCA Gates: Fault Tolerant Majority Gate

Objective:

- Develop new logic gates and circuits with emphasis on fault tolerance capabilities.
- Develop massively parallel computing architectures by exploiting inherent features of QCA.

Accomplishments:

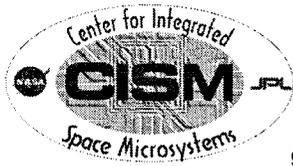
- Alternative design of highly fault tolerant logic gates based on arrays of QCA.
- Massively parallel computing architectures for a set of signal/image processing applications.

NASA Relevance:

- Enable smaller and smarter spacecraft by providing drastic improvement over VLSI technology in terms of
 - Integration density
 - Mass, volume, and power consumption
 - Radiation tolerance
 - Enabling novel applications

External Collaborators:

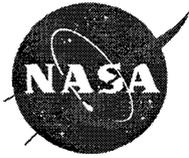
- University of Notre Dame
- Oak Ridge National Laboratory



QCA: A totally new computing paradigm

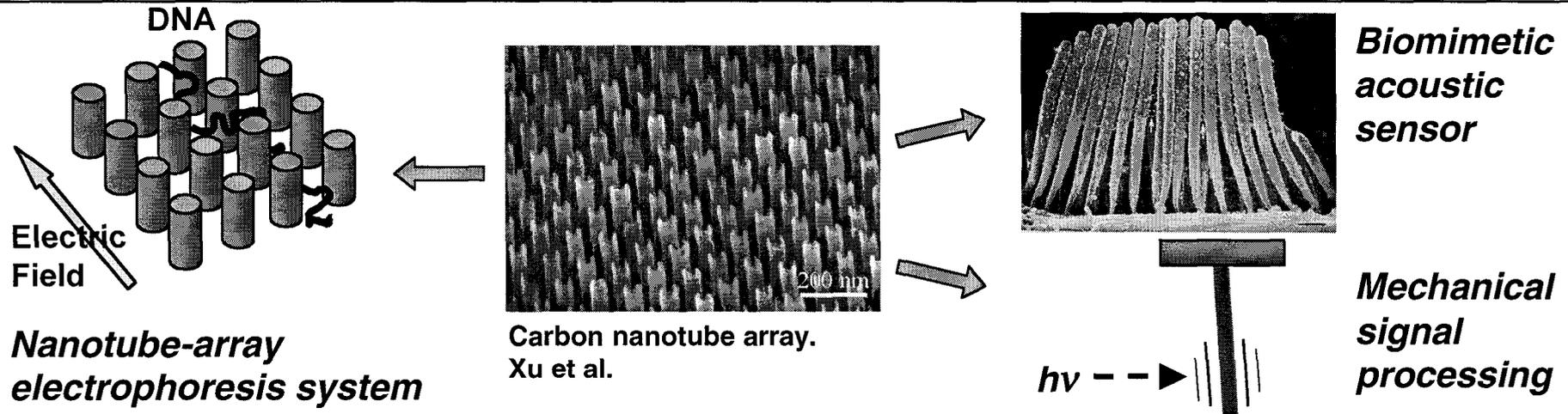
Challenges: Architecture and Application Design, Fault Tolerance





Bio-Inspired Nanotube Array Applications

Task Lead: Brian Hunt



Motivation / Impact:

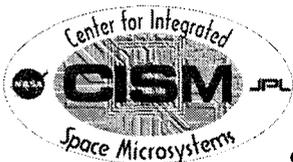
- Nanotubes combine useful properties and nanoscale dimensions
- NT-based electro-mechanical devices provide enabling technology for NASA missions: e.g., biomolecular probes, nanoexplorers

Objective:

- Demonstrate prototype nanotube-based devices***
- ♦ NT electrophoresis system
 - ♦ Biomimetic acoustic sensor
 - ♦ NT actuators
 - ♦ NT high-Q resonators
 - ♦ NT electronic components

NASA Applications:

- Search for life via acoustic and molecular signatures
- Nanoscale fabrication and characterization
- Revolutionary computing components
- Intense electron sources



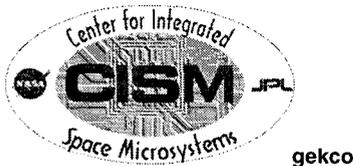
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Motivation / Customers

- **NASA Relevance:**
 - Enable devices needed for NASA missions beyond existing industry roadmap:
 - 2-5 μ m lasers and detectors
 - High density, low power computation (logic and memory)
 - Life signature biosensors
- **Impact:**
 - Low cost development of revolutionary technology.
 - Narrow empirical/experimental search space
- **Customers / Missions:**
 - CISM
 - MDL
 - HPCC





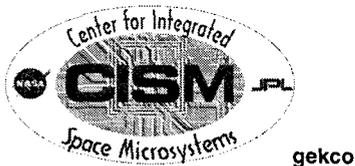
Potential Benefits / Payoffs

NASA Relevance:

- 2-5mm Lasers and detectors
- High density, low power computation (logic and memory)
- Life signature biosensors

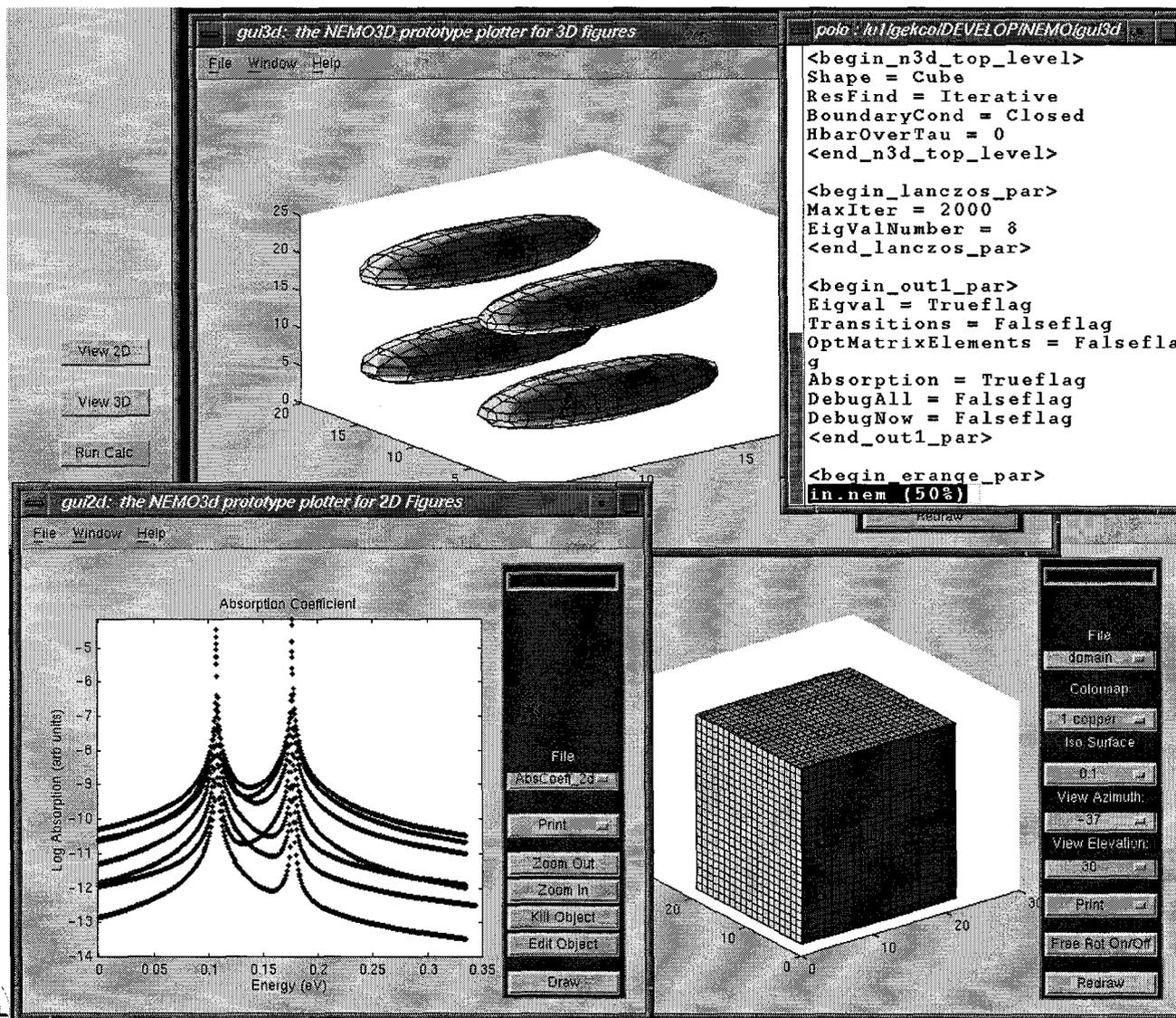
Impact:

- Narrow empirical/experimental search space
- Low cost development of revolutionary technology.





Delivery of a Simulation Tool

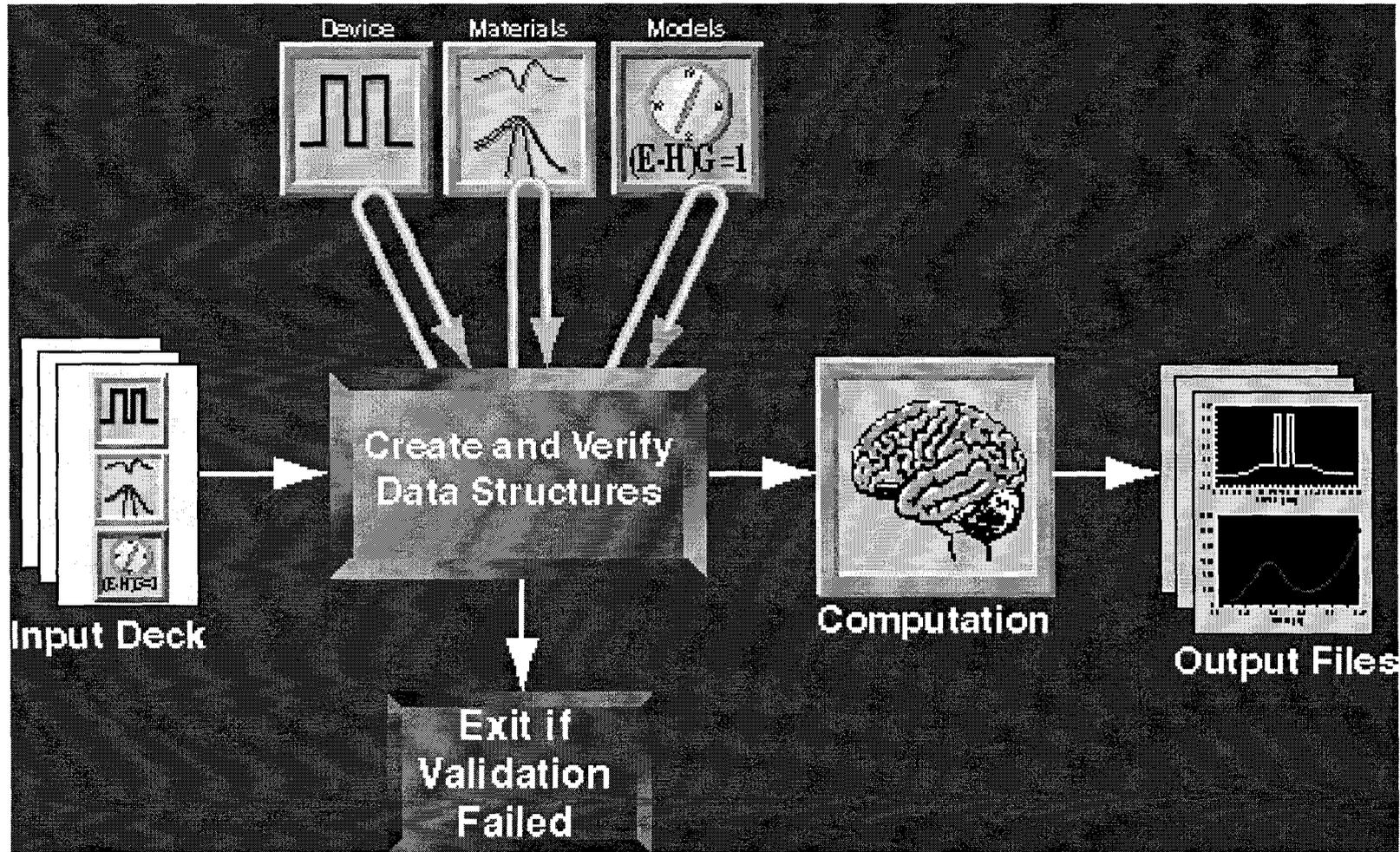


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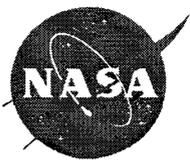


Batch Dataflow is Linear

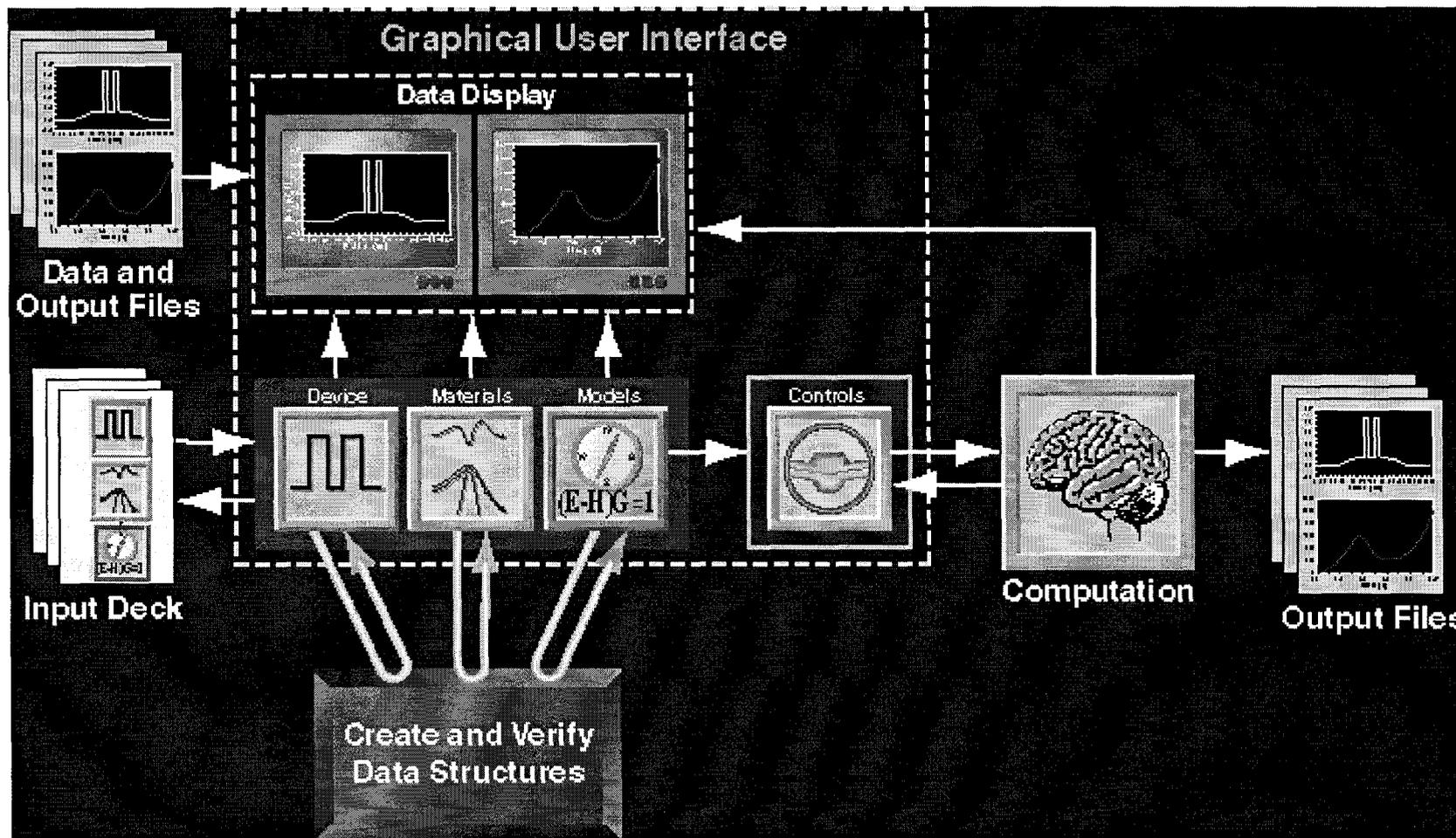


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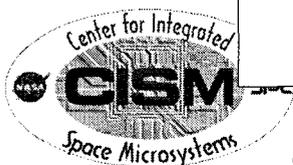




GUI Data Flow is Continuous



GUI interacts with different software blocks continuously



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Quantum Dot Modeling - Development of Bottom-Up Nanoelectronic Modeling Tool

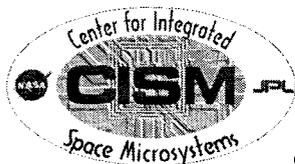
Hierarchical Ordering of User Input



Semi-class. self-cons. pot. & single band current
Specify desired outputs
Quantum region: "Where are wave-functions?"
Non-equilibrium region: "Where are the reservoirs?"
Adaptive energy grid

Quantum self-cons. potential & single band current
exchange & correlation?
how to go from bias to bias?
Specify desired outputs
Quantum region: "Where are wave-functions?"
Non-equilibrium region: "Where are the reservoirs?"
Quantum Charge region: "Where is the charge quantum mechanically calculated?"
Resonances-based energy grid

Ask user for input that is really needed.
 -> User input determines the sequence of simulation parameter windows.



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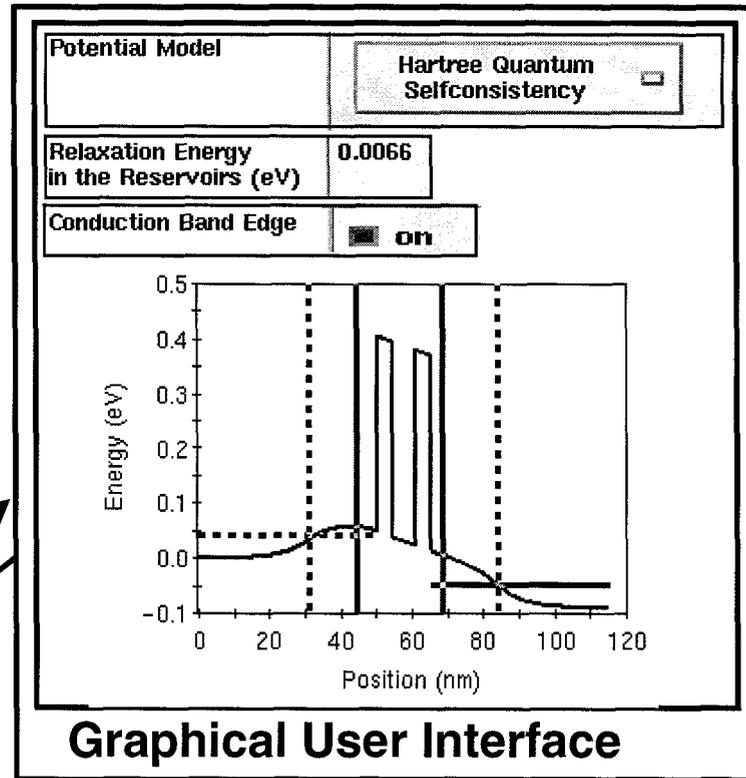


Generic Data Structure I/O



Dynamic GUI Design.

- data structure
- member descriptor
- > I/O for GUI or files



File/Batch User Interface

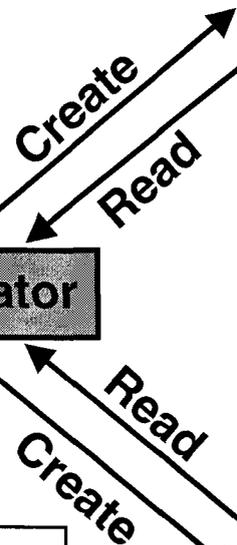
```
potential=Hartree
hbarovertau=0.0066
Ec=FALSE
< start=45, end=69 >
```

Data Structure
 PotType potential
 real hbarovertau
 Boolean Ec
 RangeStruct NonEq

Translator

Theorist

Software Engineer



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