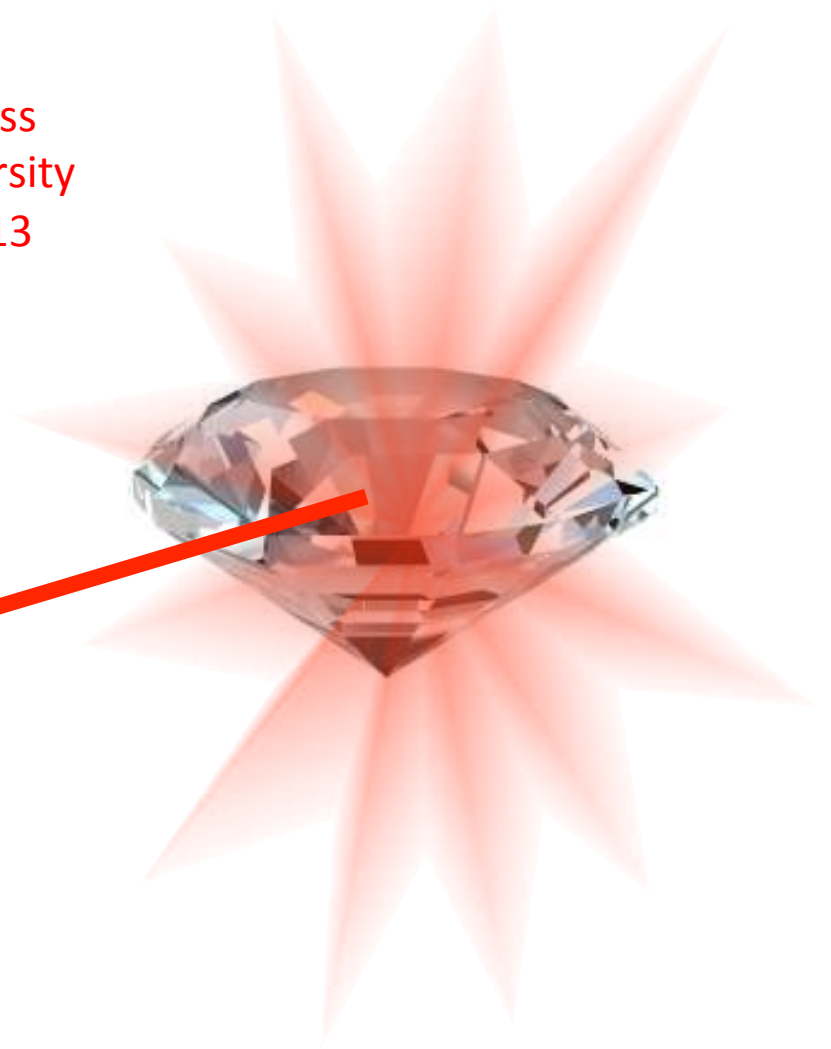
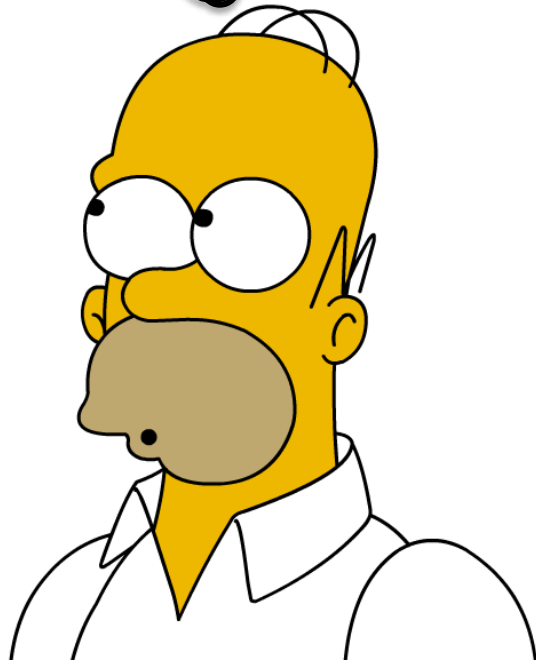
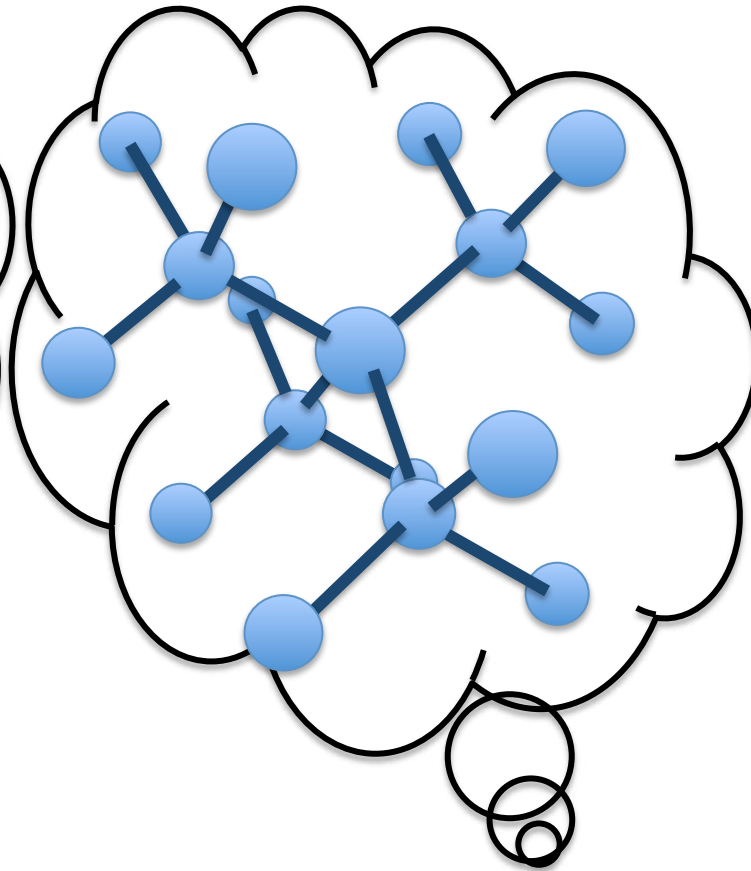


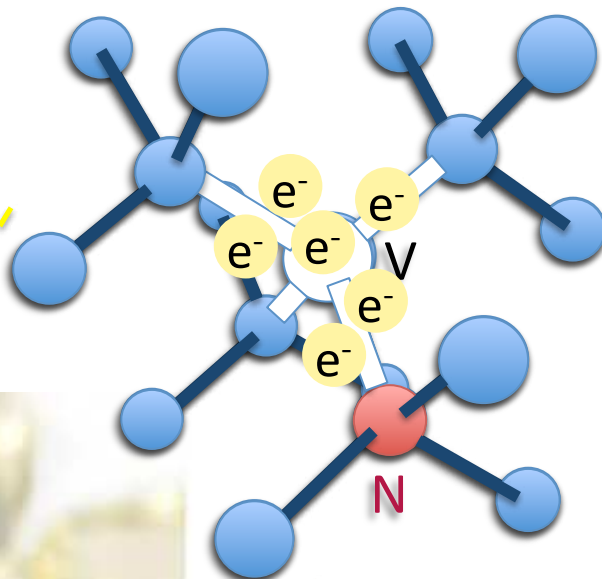
# Shooting lasers at diamonds

Lily Childress  
McGill University  
April 5, 2013

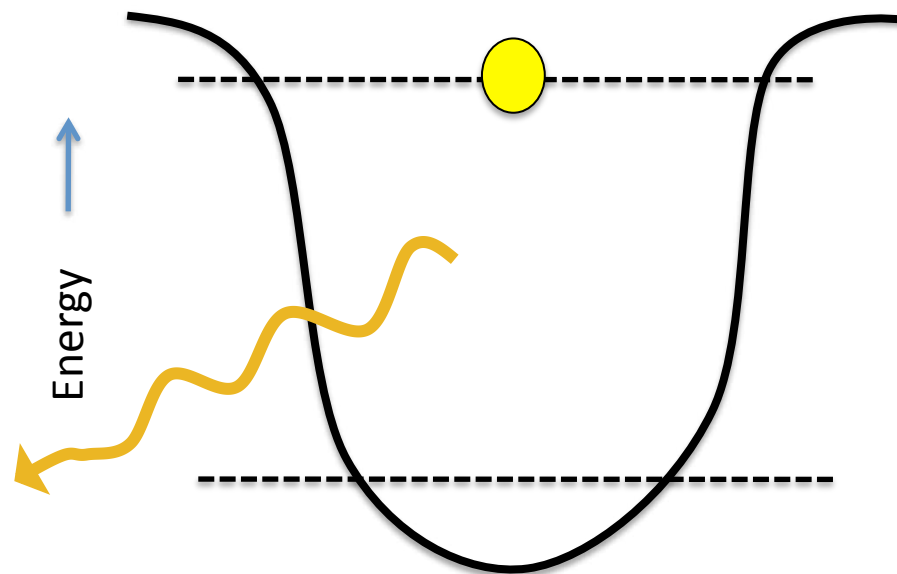
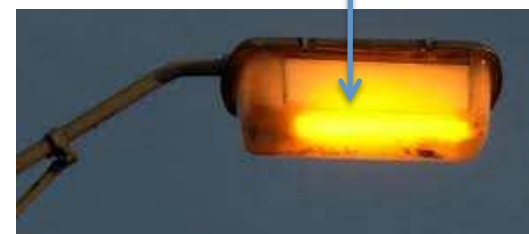




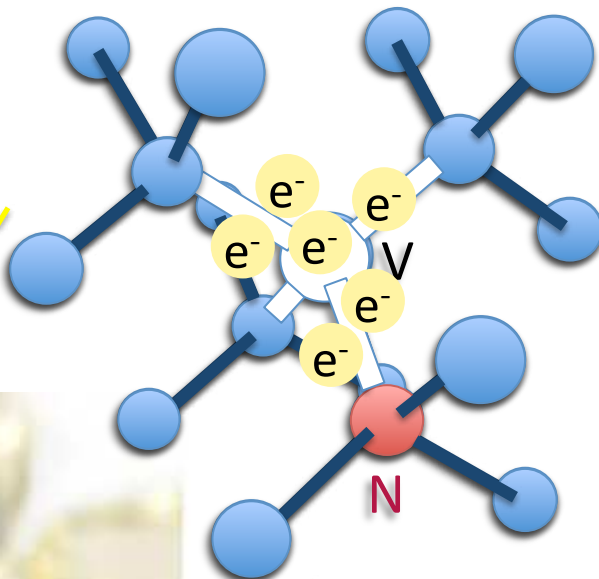
# Defects in Diamond



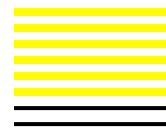
Sodium atoms



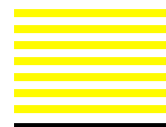
# Defects in Diamond



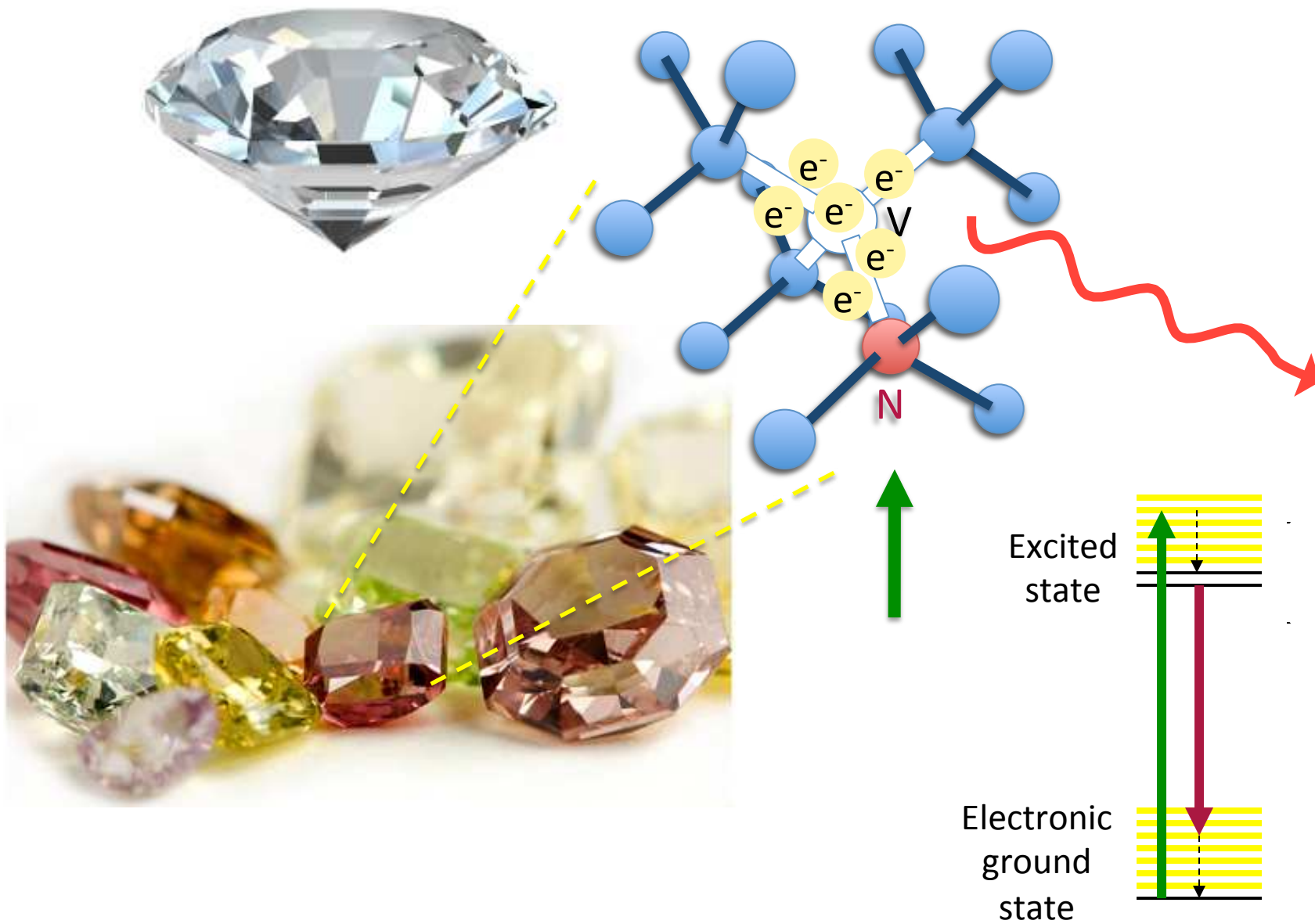
Excited state



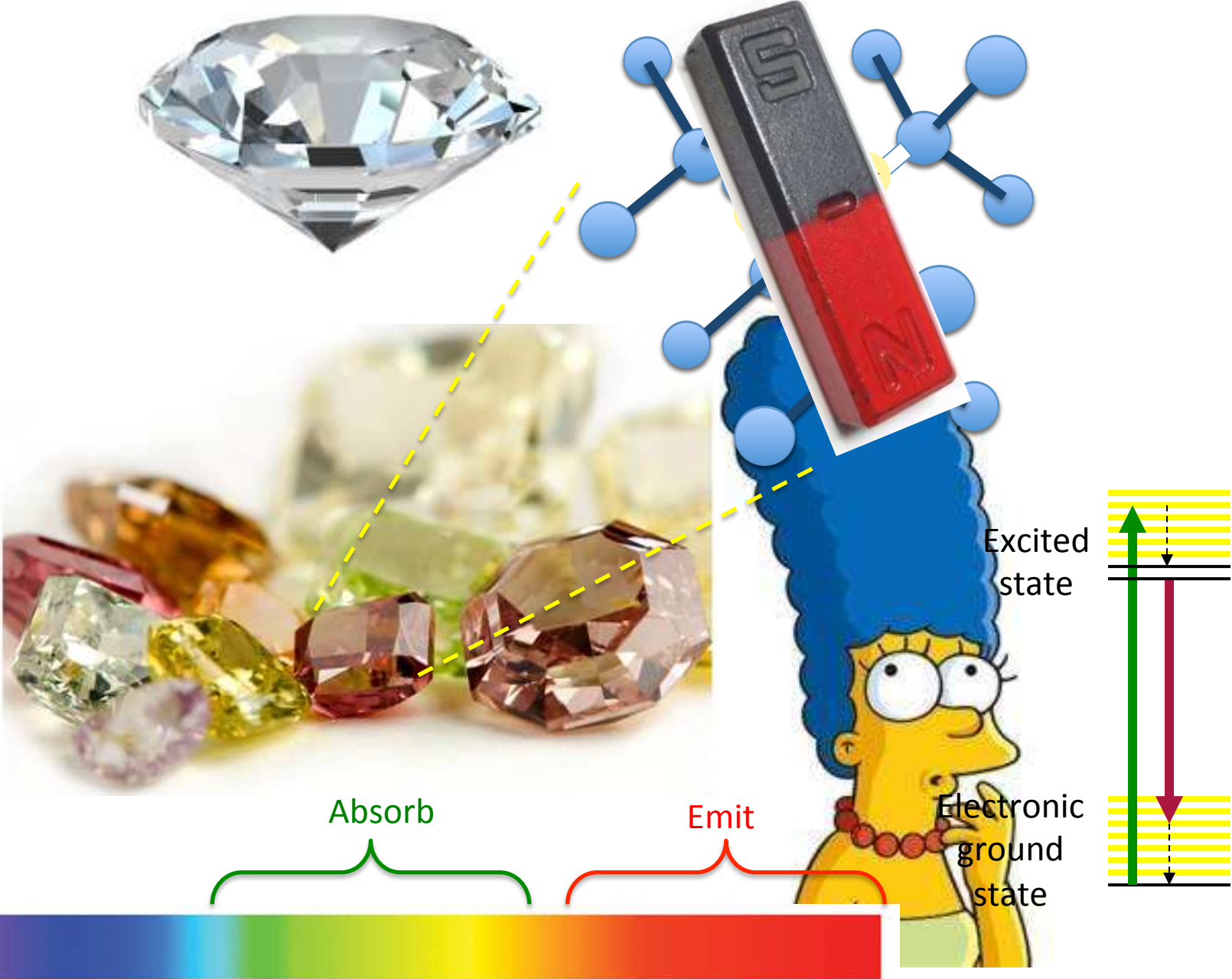
Electronic ground state



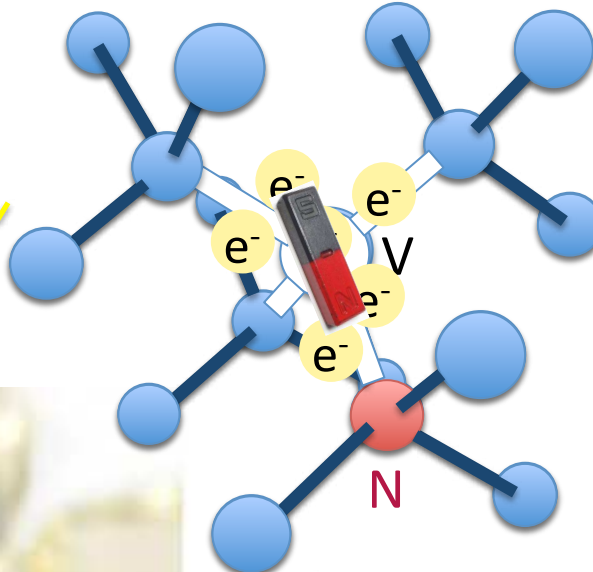
# Defects in Diamond



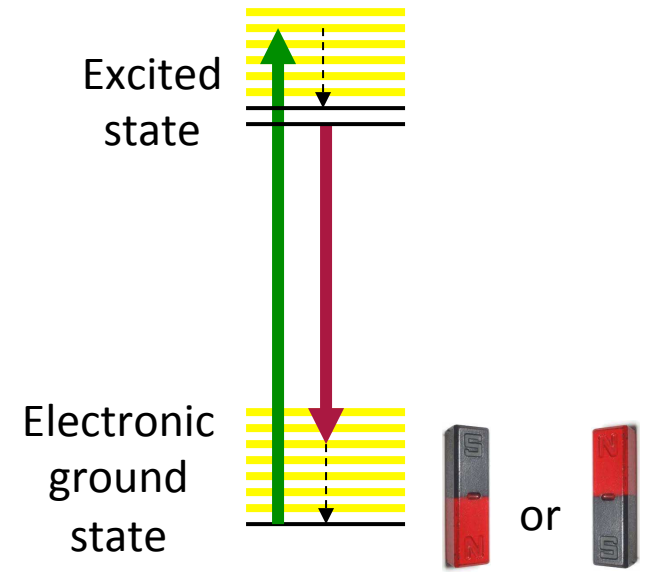
# Defects in Diamond



# Defects in Diamond



Spin  
= tiny, quantized  
magnetic moment  
= a place to store  
information  
= (maybe, someday)  
a quantum bit



# Quantum Bit



= logical "0"



= logical "1"

Mmm...Qubits!





## Classical bit

0 or 1

## Quantum bit

$|0\rangle$  or  $|1\rangle$  or  $|0\rangle + |1\rangle$   
or  $a|0\rangle + b|1\rangle$

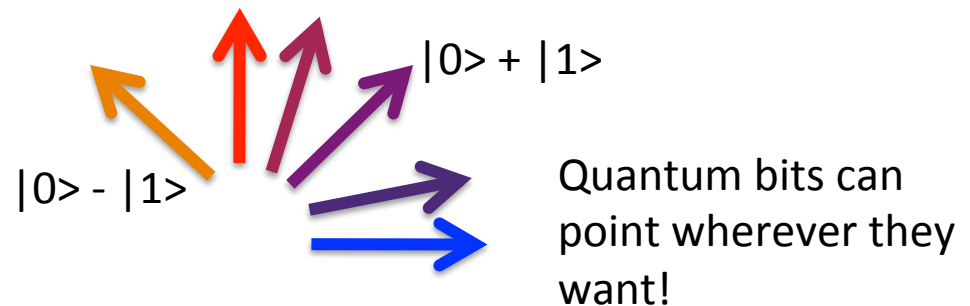
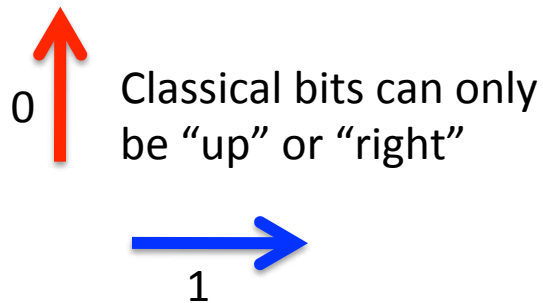
States that are both  $|0\rangle$  and  $|1\rangle$



It's not just a "probability" to be a 0 or a 1, these states really are both at the same time

And there's more:  $|0\rangle + |1\rangle$  is different from  $|0\rangle - |1\rangle$

## An analogy to directions:



## Two bits?

Four options: 00 10  
01 11

Two quantum bits could be in all four states at once

$|00\rangle + |01\rangle + |10\rangle + |11\rangle$

# Why is this useful?

...an example to give you a flavor...

Suppose you wanted to know who had crank called you, and all you had was caller ID and a phone book with 10,000 people in it

You'd have to check nearly every entry!  
– On average, about 5000 tries!

“Moe” = 00010110000011

“Homer” = 10000110100000

“Marge” = 01100110000100

...  
And 9,996 more possible names

“Bart” = 01100110000111



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...  
And 9,996 more possible names

“Bart” = 01100110000111



But what if you could do this with quantum bits?

# Why is this useful?

...an example to give you a flavor...

Suppose you wanted to know who had crank called you, and all you had was caller ID and a phone book with 10,000 people in it



“Moe” = |00010110000011>



“Homer” = |10000110100000>



“Marge” = |01100110000100>



...  
And 9,996 more possible names

“Bart” = |01100110000111>



# Why is this useful?

...an example to give you a flavor...

Suppose you wanted to know who had crank called you, and all you had was caller ID and a phone book with 10,000 people in it



Use a superposition state!

"Moe" =  $|0001011\text{No}0011\rangle$

+

"Homer" =  $|10000\text{No}100000\rangle$

+

"Marge" =  $|011001\text{No}00100\rangle$

+

...  
And 9,996 more possible names

-

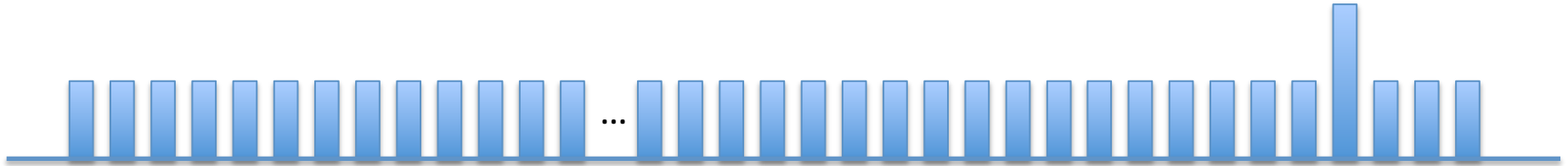
"Bart" =  $|011001\text{Yes}0111\rangle$



A "picture" of the algorithm in terms of the amplitudes of different quantum states:



A “picture” of the algorithm in terms of the amplitudes of different quantum states:



...after 100 repetitions:

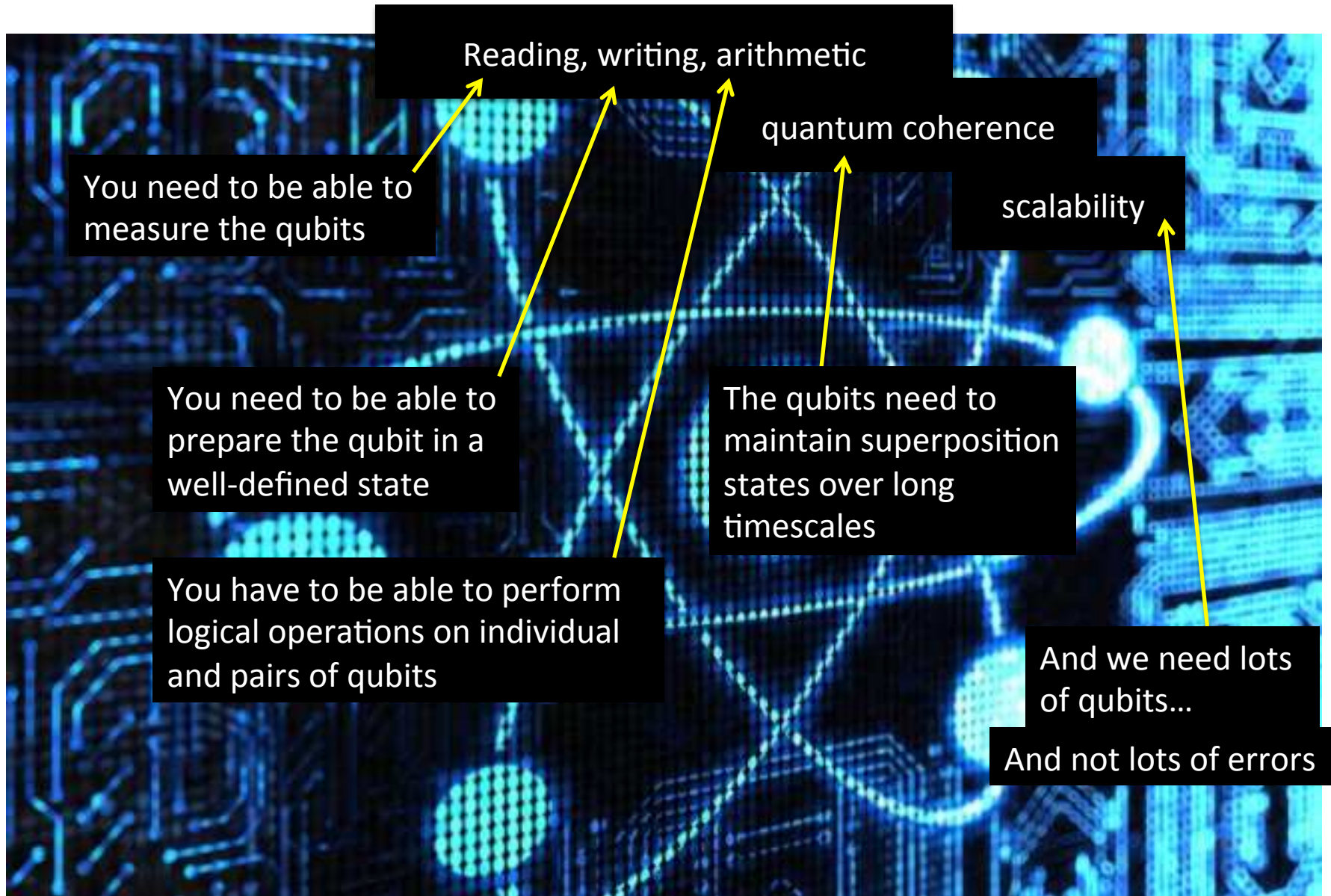


|01100110000111>

Only 100 tries to search 10,000 entries!



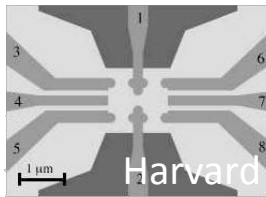
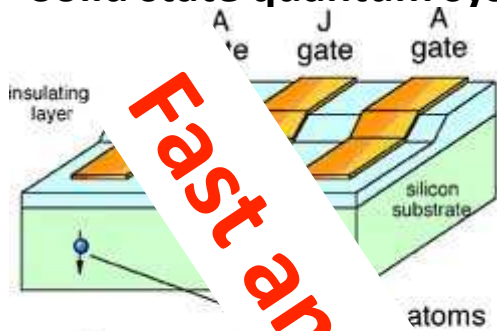
# The Quest for Quantum Computation



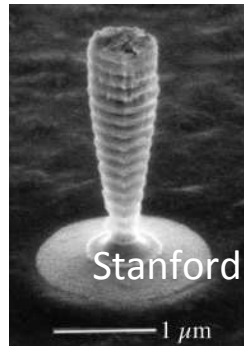
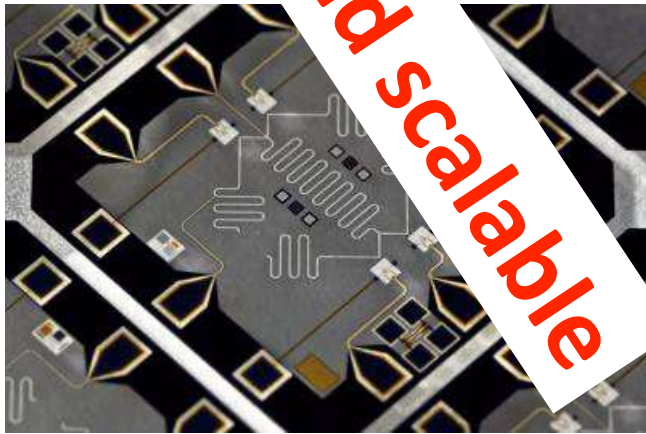


# The Quest for Quantum Computation

- Solid state quantum systems



atoms



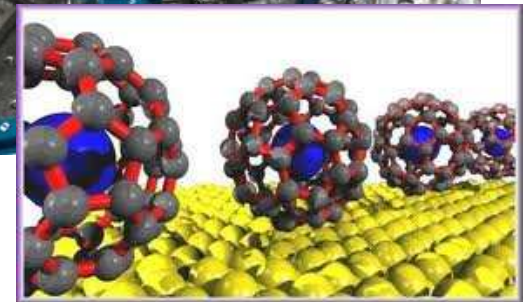
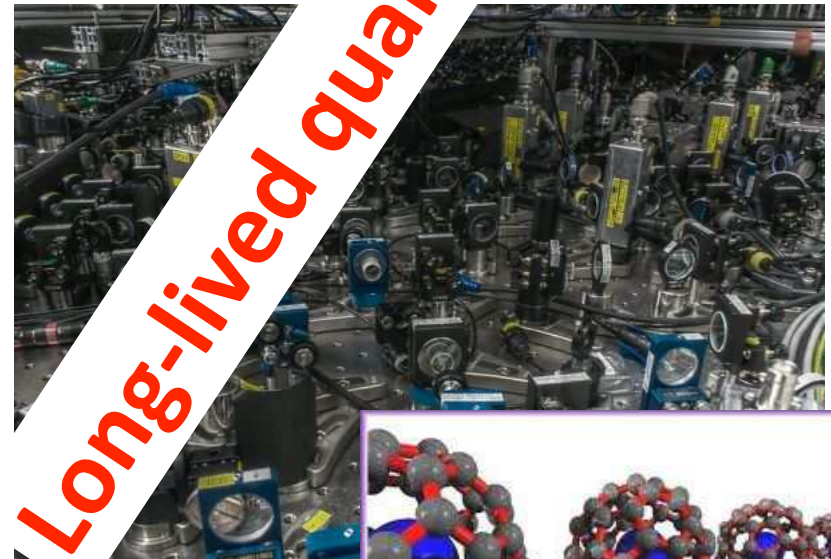
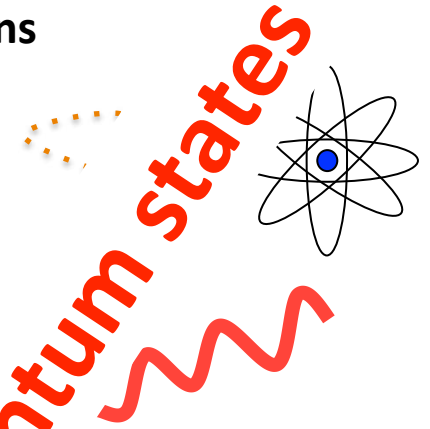
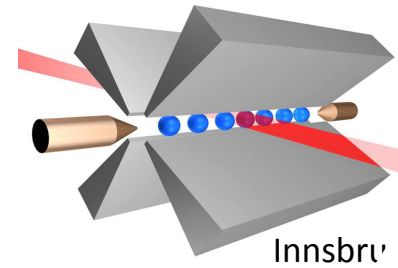
- Defects in diamond



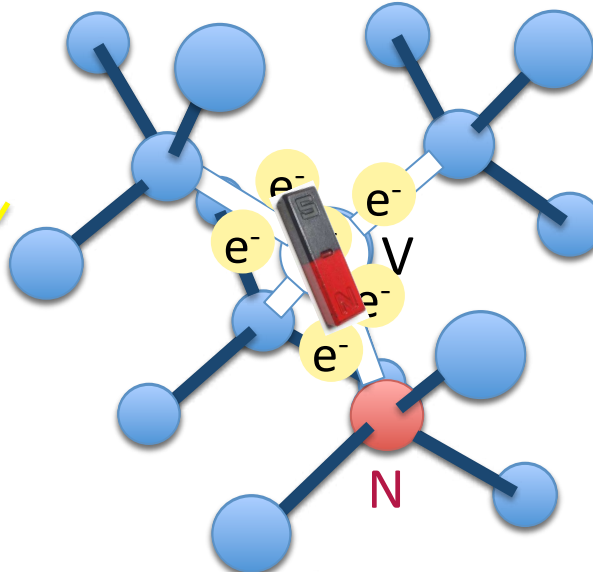
**Both?**



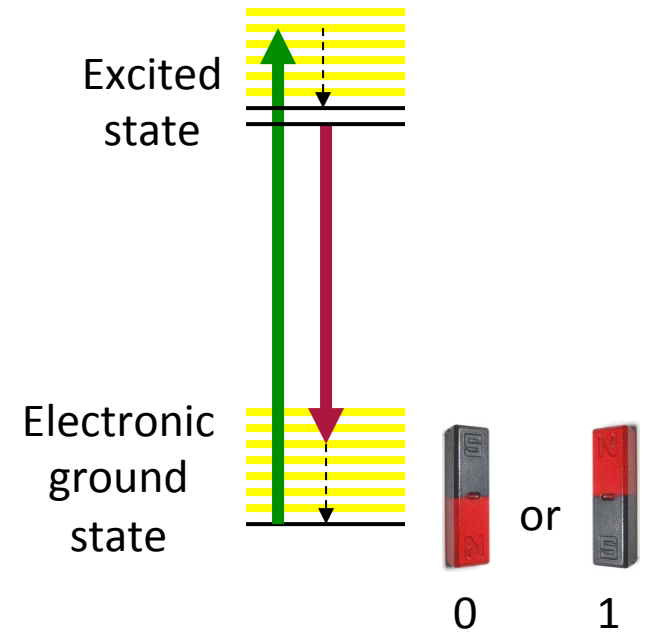
- Atoms & molecules, isolated nuclear spins, photons



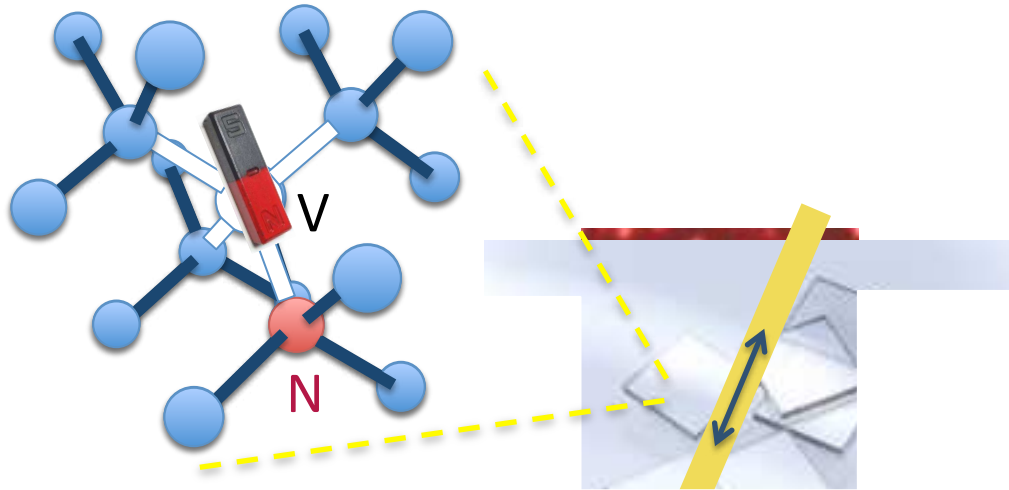
# Defects in Diamond



Spin  
= tiny, quantized  
magnetic moment  
= a place to store  
information  
= (maybe, someday)  
a quantum bit

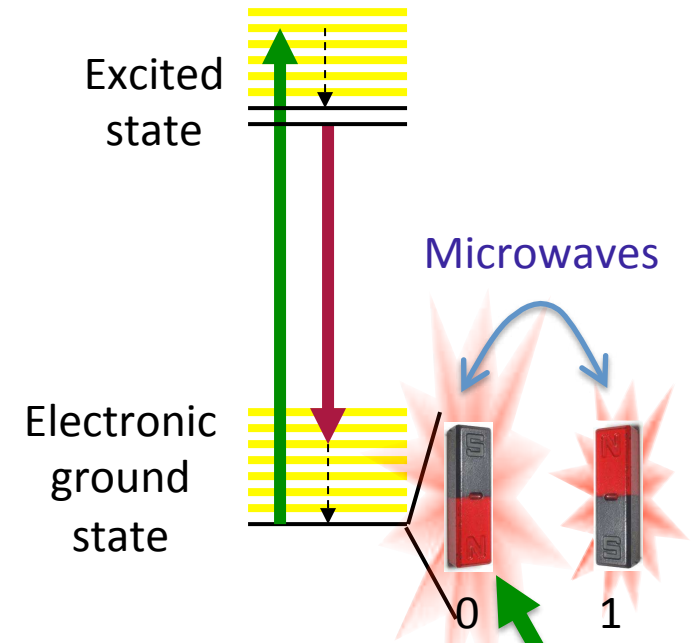


# The NV center as a qubit

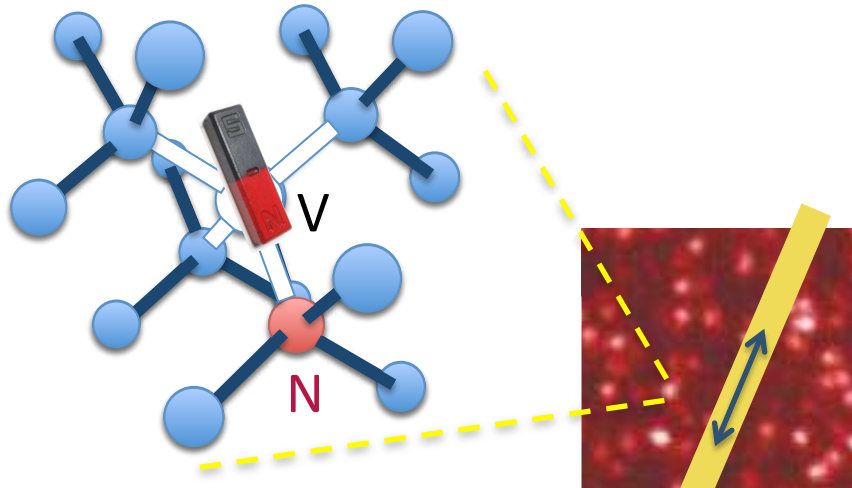


Oscillating microwave current  
→ oscillating magnetic field  
→ torque on the spin

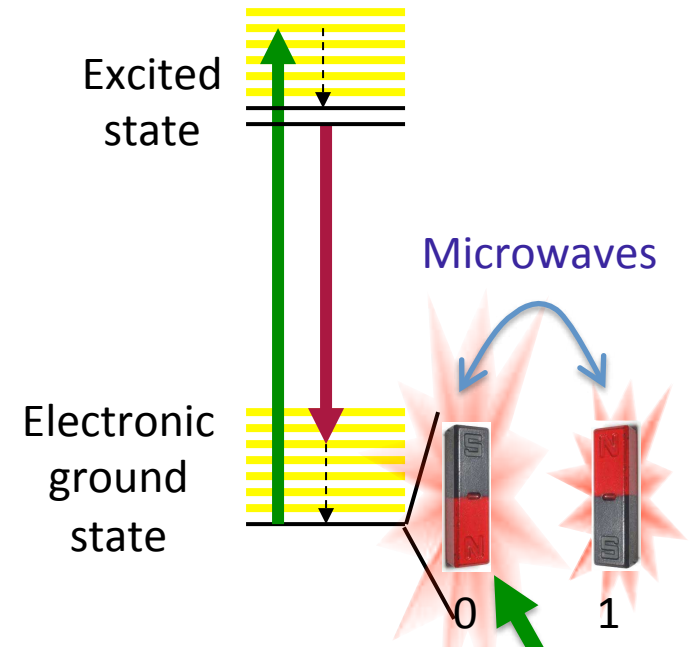
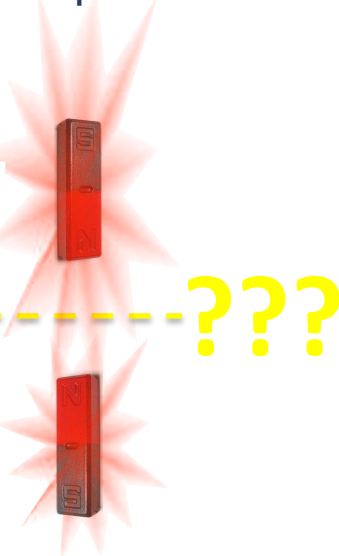
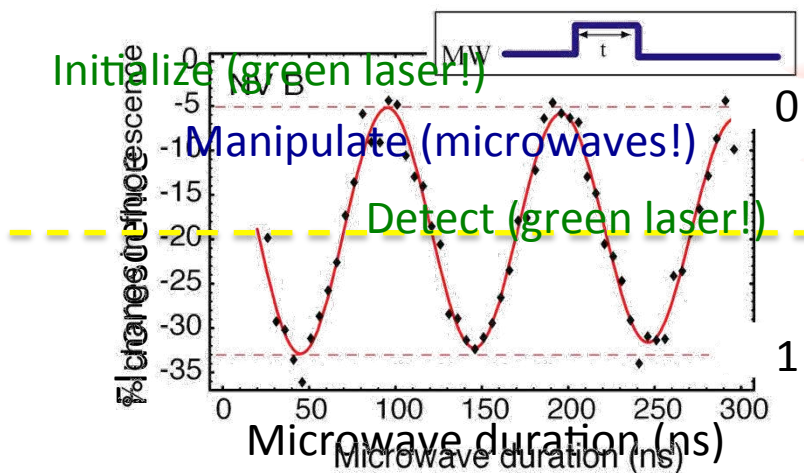
- ✓ Single-defect isolation  
**Look at one bit**
- ✓ Optical qubit detection  
**Read it out**
- ✓ Optical qubit preparation  
**Initialize it (write)**
- ✓ Fast qubit manipulation  
**Control it**



# The NV center as a qubit

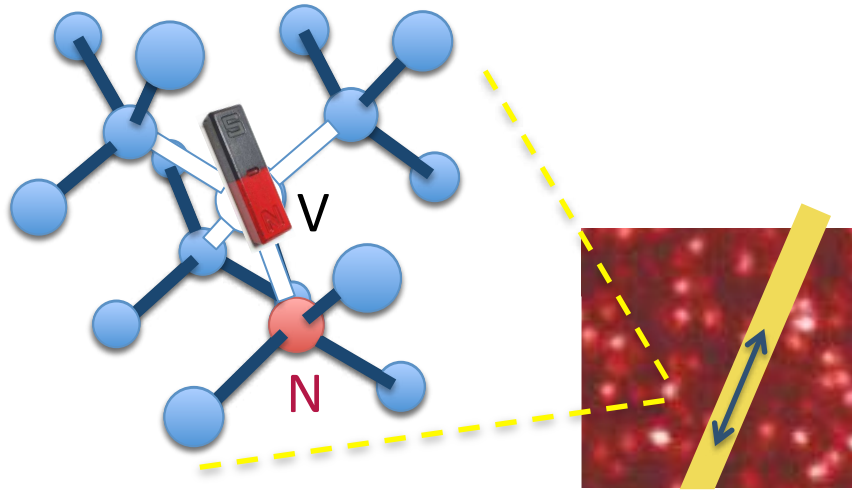


Oscillating microwave current  
 → oscillating magnetic field  
 → torque on the spin

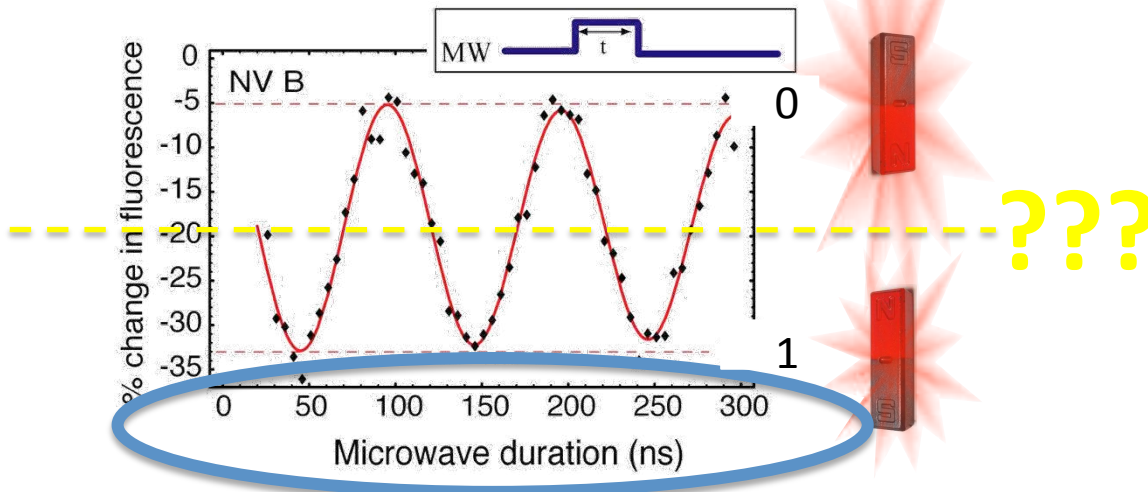


- ✓ Single qubit isolation
  - ✓ Readout at one bit
  - ✓ Optical readout and detection
  - ✓ Optical qubit manipulation (Initialization, Arithmetic)
  - ✓ Fast qubit manipulation
- Control**

# The NV center as a qubit



Oscillating microwave current  
 → oscillating magnetic field  
 → torque on the spin



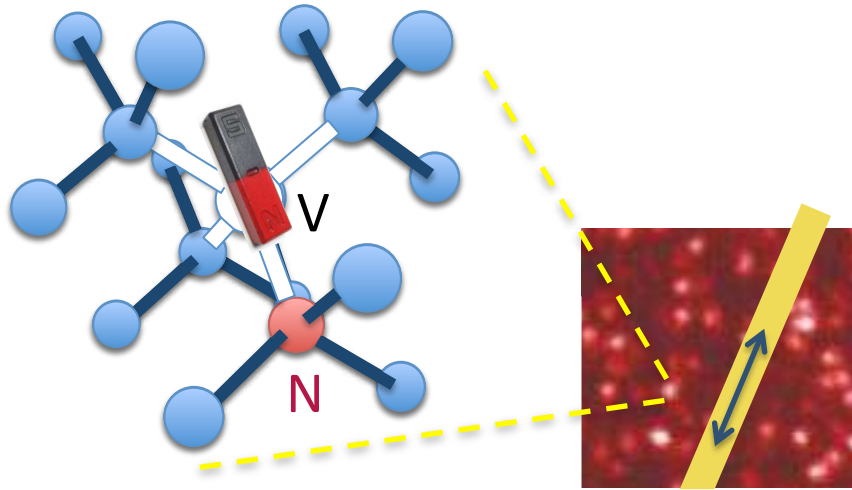
✓ Single qubit isolation  
 ✓ Optical readout at one bit  
 ✓ Optical control and detection  
 ✓ Optical qubit initialization  
 ✓ Fast readout (100 ns)  
 ✓ Fast quantum coherence

Microwaves

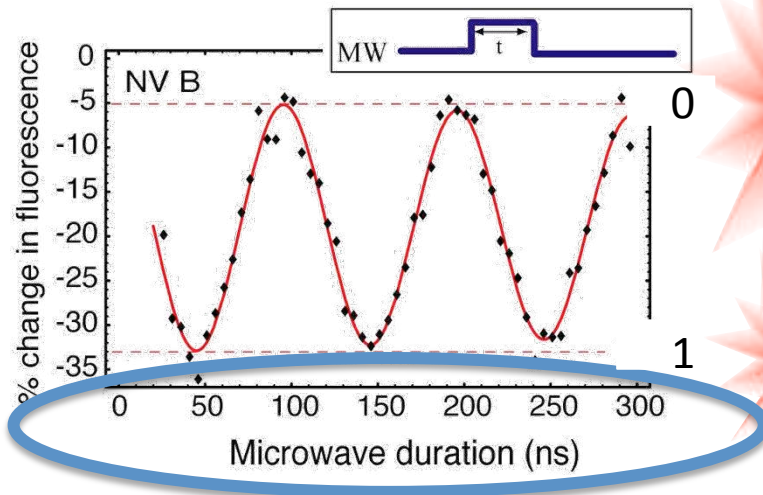


These sinusoidal oscillations indicate quantum coherence!

# The NV center as a qubit



Oscillating microwave current  
 → oscillating magnetic field  
 → torque on the spin



- ✓ Single qubit isolation
- ✓ Read, write, and detection of one bit
- ✓ Optical readout and detection
- ✓ Optical control and readout
- ✓ Fast quantum operations

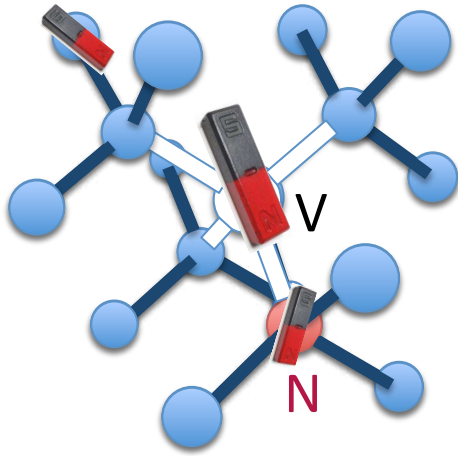
Reading, writing, and arithmetic  
 quantum coherence

Possible to maintain coherent operation for milliseconds!

(and longer at low temperatures)



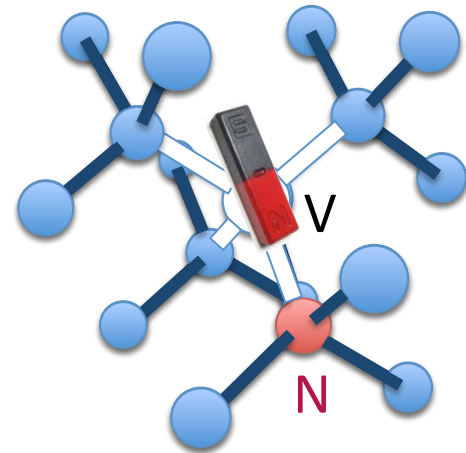
But what about scalability ?



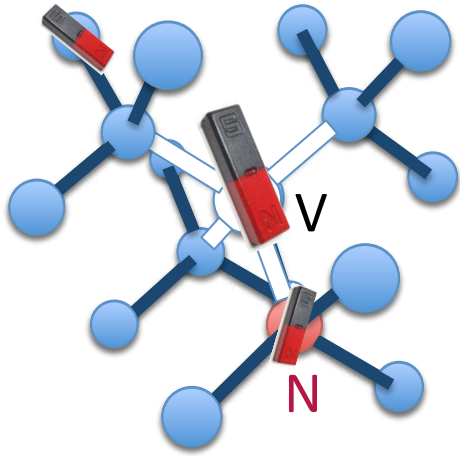
Auxiliary qubits:  
nuclear spins

scalability ?

**~ 10 nanometers apart!**  
How can you individually  
detect and manipulate them?  
(You can't even resolve  
them in a microscope)

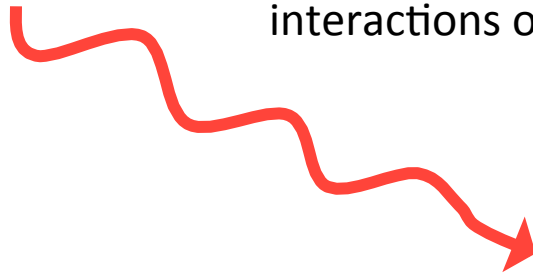


But what about scalability ?



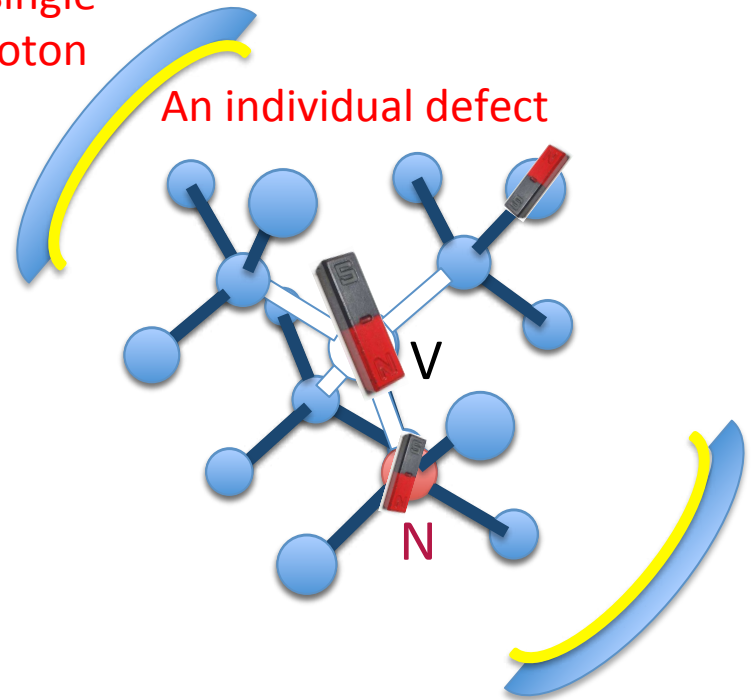
Auxiliary qubits:  
nuclear spins

Could we use light to create effective interactions over long distances?



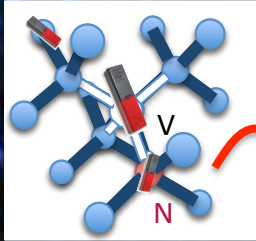
A single  
photon

An individual defect



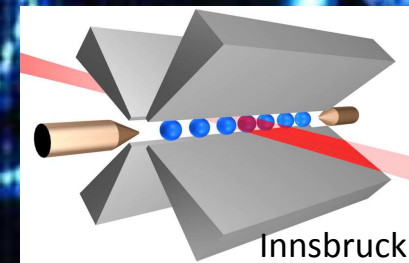
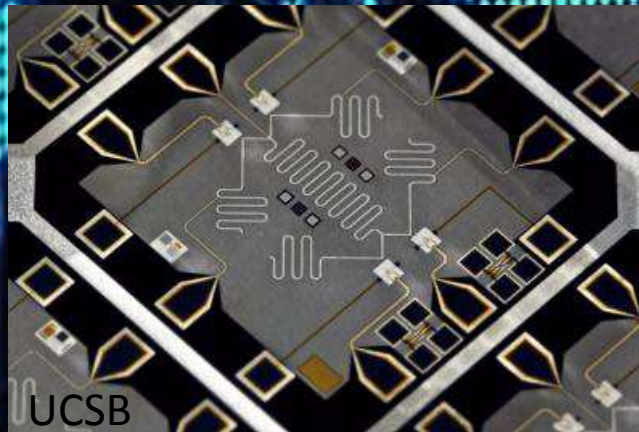
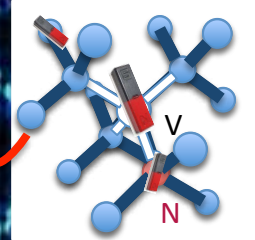


# Is this all really going to happen?



Need:  $\ll 1\%$  error  
Few % errors

Photonic channel  
Need:  $\ll 10\%$  error  
30% errors  
And 10 minutes...



Thank you!

