What can Computer Science learn from Biology in order to Program Nanobots safely?

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history

- self-replicating machine
    - John von Neumann, 1950s
  - 29-state Cellular Automaton
    - demonstrates the principle of a "Universal Constructor"
      - abstract design: ignores problems of raw material transport, selection, and manipulation

- "There's Plenty of Room at the Bottom"
    - Richard P. Feynman, 1959
  - manufacture on the atomic scale
    - placing atoms precisely

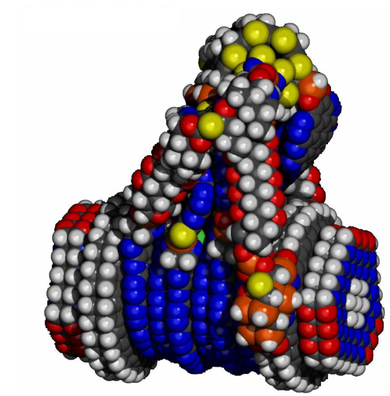
nanotechnology

- ***molecular nanotechnology (MNT)*** [K. Eric Drexler, 1986, 1992]
  - molecular scale programmable “robots”, mechanically positioning reactive molecules
    - making macroscopic artefacts
    - potentially revolutionary technology
  - “molecular manufacturing”

- macroscopic nanotechnology
  - electron microscopes moving atoms around
  - very clever, precise fabrication technologies
    - but just incremental improvements?

assemblers

- assemblers, nanites, nanobots
    - molecular scale robots
  - making macroscopic artefacts
    - assembling anything, from steaks to spaceships
- assemblers make conventional factories unnecessary



- CS challenges:
  - software, tools, techniques, models, ...
    - hardware/wetware up to physicists, engineers, biologists
  - ***but those CS tools will require bio-inspiration***

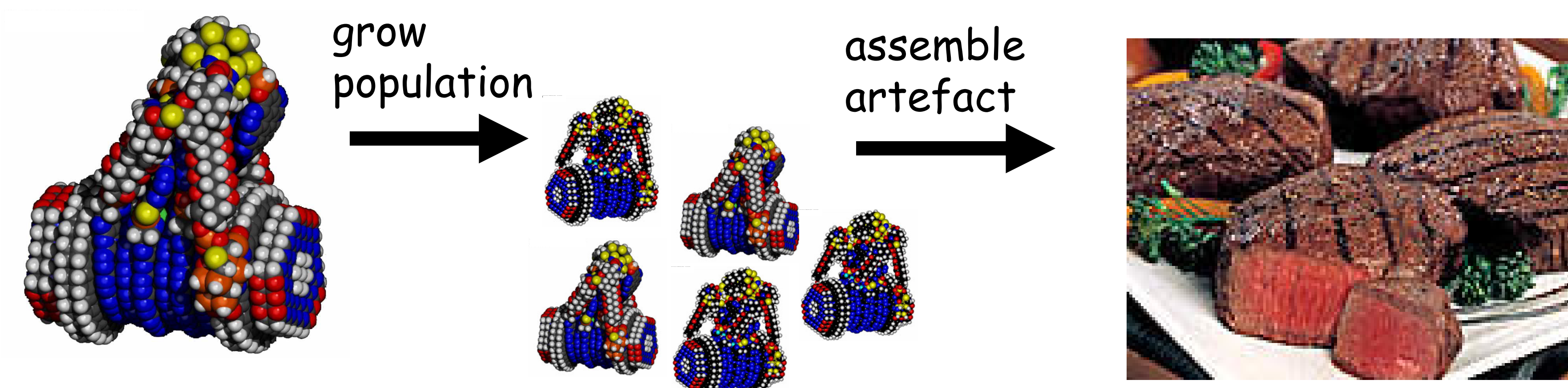
nanoscale fabrication

- "desktop" fabrication plant, comprising
  - many very small devices
    - trillions of molecular scale robot assemblers, conveyors, manipulators, …
  - original conception: centralised computer control
      - electrical, mechanical, chemical, …
    - assembly instructions broadcast to all the robot assemblers
    - each assembler has some local state to customise the instructions

- universal assembler
  - given the right assembly instructions, and the right raw materials, the plant can assemble *anything*
  - ***DNA "instructions" + material in cells "assemble" an organism***

assembling artefacts

- growth and development on two levels
  - bootstrap a small initial assembler population
    - pool of raw material (mainly carbon)
    - assemble trillions of nanites (exponential growth)
  - eg, to build a new nano-fabrication plant
    - which then assembles, or "grows", the artefact



http://www.imm.org/

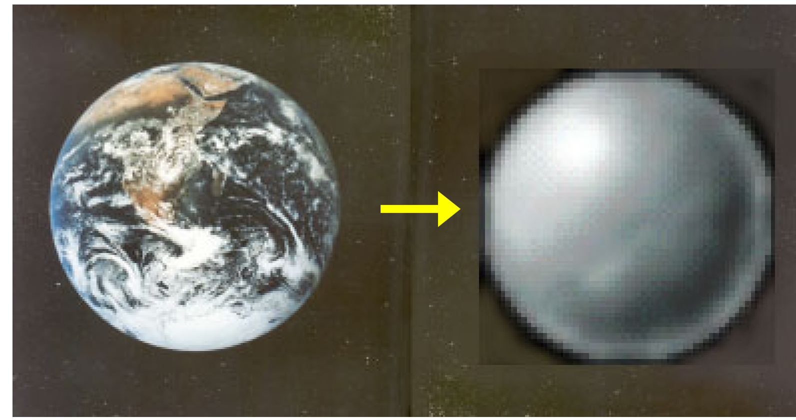
http:// www.omahasteaks.com/

disassemblers

- as part of assembly
  - disassembly of raw materials required for assembly
  - disassembly of “scaffolding” required during assembly
- medical applications
  - scouring cholesterol from arteries
  - filtering blood toxins
  - removing damaged cells
  - repairing damaged nerves
- environmental applications
  - disassembling toxic chemicals into safe constituents
  - concentrating heavy metals
  - disassembling unwanted artefacts

when nanites go bad

- “grey goo” scenario
  - where replicating nanites escape, go rogue, and disassemble the planet



- “Some Limits to Global Ecophagy by Biovorous Nanoreplicators” -- Robert A. Freitas

http://www.foresight.org/NanoRev/Ecophagy.html

Foresight Institute guidelines (excerpt)

- Artificial replicators must not be capable of replication in a natural, uncontrolled environment.
- Evolution within the context of a self-replicating manufacturing system is discouraged.
- Any replicated information should be error free.
- Any self-replicating device which has sufficient onboard information to describe its own manufacture should encrypt it such that any replication error will randomize its blueprint.
- Mutation (autonomous and otherwise) outside of sealed laboratory conditions, should be discouraged.
- MNT device designs should incorporate provisions for built-in safety mechanisms, such as: 1) absolute dependence on a single artificial fuel source or artificial "vitamins" that don't exist in any natural environment; …

http://www.foresight.org/guidelines/current.html

evolution happens

- given vast numbers of nanites, some will *go wrong*
  - if they are self-replicating, they will evolve
    - evolution is an inevitable consequence of "reproduction, variation, selection"
- safety critical application
  - current approaches totally inadequate
    - "proof of correctness" doesn't help with a mutant
  - new safety techniques and tools required
    - *design* of non-viable "adjacent possible"
      - Foresight Institute guidelines are an excellent start
    - evolution will exploit *anything*
      - even (especially) things outside your abstract model

is MNT possible?

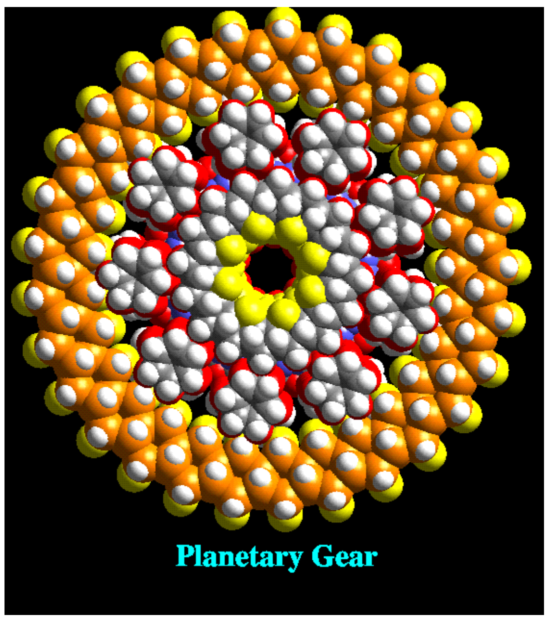
- "it violates fundamental laws of physics/chemistry …"
  - thermal noise
  - 2nd Law of Thermodynamics
  - quantum effects
  - chemical reaction pathways
  - …
- but we have an existence proof : us !
  - living organisms are "assembled" (grown) from the molecular level up
  - ***we need to understand these bio-processes***
    - ***how does DNA "instruct" for "building" an organism?***
    - ***what more than just DNA is necessary?***
      - ***raw materials, signalling mechanisms, dynamics, …***

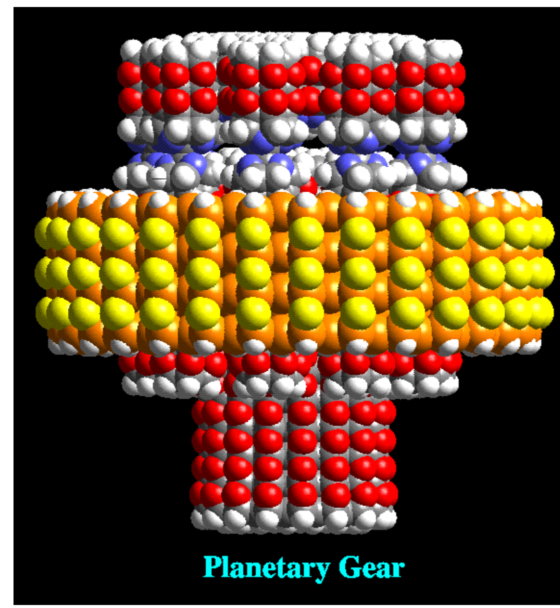
wet *v.* dry chemistry

- the organic assembly process uses “wet chemistry”
  - proteins, enzymes, etc, in aqueous medium
  - this wet chemistry is difficult to *control* precisely
    - water has *incredibly* complicated chemistry
    - proteins are “floppy”
    - …
- molecular nanotechnologists propose “dry chemistry”
    - *eg*, molecular vapour deposition, used in semiconductor manufacture
  - dry chemistry is (probably) much more *controllable* than wet chemistry
  - able to build things that biology would find difficult
    - look to material science
    - “diamondoid” constructions, from manipulating carbon atoms

planetary gear (simulation)

- transfer a rotational impulse from the input to the output unit, one input cycle in 12 picoseconds (0.012 ns)



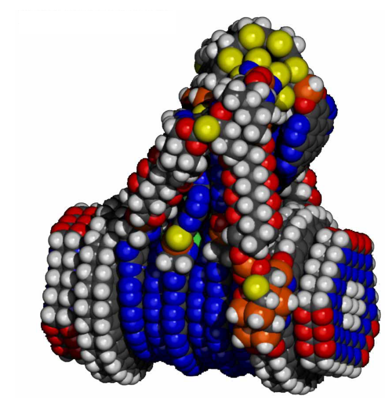


http://www.wag.caltech.edu/gallery/gallery_nanotec.html

the MNT design challenge

- assembled artefact is *emergent property*
  - of actions of vast number of nanites
- design requires "reverse emergence"
  - from desired emergent artefact
  - to behaviour of nanite assemblers

design appropriate assemblers



is MNT feasible?

- “emergent properties are in general unpredictable, so the whole endeavour is flawed”
- … but, not interested in *arbitrary* artefacts
  - beware a Gödel fallacy
    - cf. Halting Problem v. proofs of program termination
    - cf. No Free Lunch theorem
- find *classes* of emergent properties
  - need only a sufficient theory
    - patterns of emergence, inspired by real world

We can never hope to predict the exact branchings of the tree of life, but we can uncover powerful laws that predict and explain their general shape.
-- Stuart Kauffman, 1995

transferable technology?

- do we have any reason to believe *bio-inspired* algorithms will be any good for designs for assembling *artificial* constructs?

- observation : we, the designers, are also (an evolved) part of the biological world

- ***conjecture*** : because of this, maybe our "artificial" problems are not totally arbitrary, but sufficiently "close" to real biology that the insights are transferable?

CS/bio understanding for MNT (1)

- complex systems
  - simple rules give complex behaviour
    - but *which* simple rules give the *desired* complex behaviour?
  - designing the desired emergent properties
  - designing the lack of undesired emergent properties
- thorough understanding of complex systems
  - ***biology provides many exemplars, from gene regulatory networks, via organisms, to ecosystems***
- searching for suitable designs
    - large complex search space
  - ***bio-inspired evolutionary search algorithms***

CS/bio understanding for MNT (2)

- growth and development
  - self-replicating nanites
  - assembly as "growing" the final artefact
    - how and what local growth rules result in what global structure
    - ***embryonics***
    - ***development of infant to adult***
    - ***use of "scaffolding"***
    - ***role / necessity of death***
  - self-repair as a feature of continual growth?

- growth of *safe* designs
  - "design out" the grey goo
    - ***errors, mutation, progress of evolution***
    - ***pathogens, attacks and defences***

CS/bio understanding for MNT (3)

- embodied nanites
  - strange physics at very small sizes
    - friction, flow, etc all very different
  - constraints of embodiment on structure and growth
    - ***viability at all development stages*** too constraining?
  - inevitability of evolution
    - ***evolution exploiting physical embodied properties***

two way trade

- what biology don't we know about that could be useful?
  - what biology might *look* useful, but is actually too "bio-centric"?

- could our work help biology?
  - provide insight into necessity v. contingence?
    - what biology is necessary for correct robust functioning
    - what is necessary only for the particular physical realisation
      - organic, carbon-based lifeforms
    - what is merely contingent evolutionary aspects?
      - "playing the tape twice"
  - provide insight from different complex systems?