Primitive Molecular Manufacturing

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Small is Beautiful

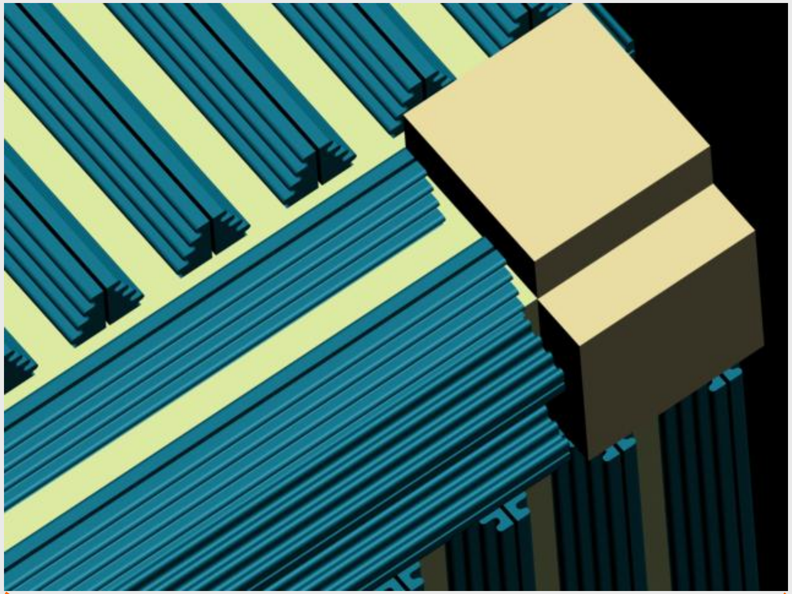
- Scaling laws: throughput ~ size^-4
  - 10 cm tool: 3 GY. 100 nm tool: 100 sec.
- Power density ~ size^-1
- Digital logic likes to be small
- Access atoms → Digital construction
- Low wear, high strength, superlubricity
- Digital design bottom-up, like computers

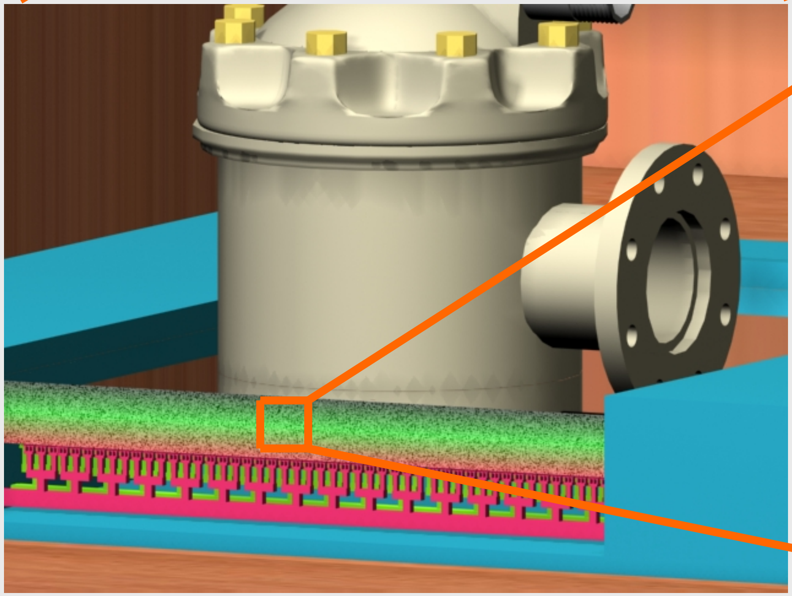
Molecular Manufacturing

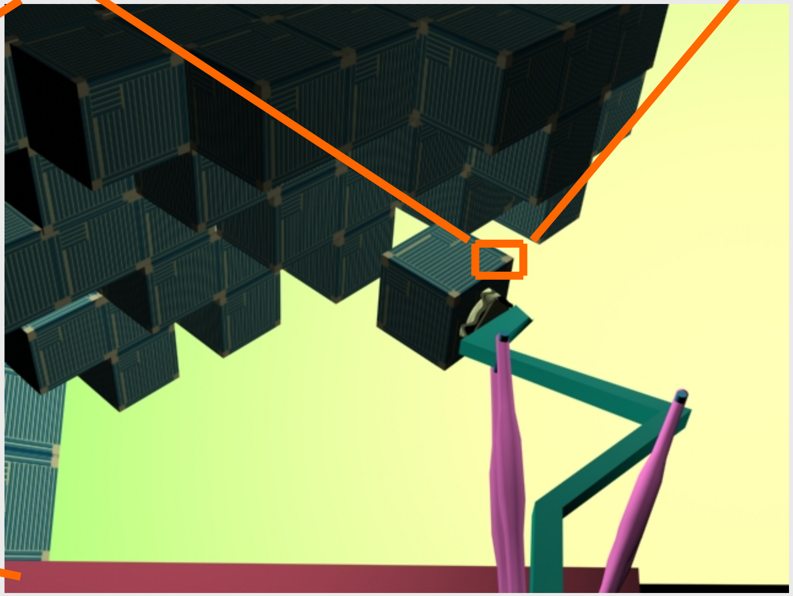
- Building precise, useful nanoscale structures with nanoscale tools
- Engineering approach to nanoscale
  - Molecular fabrication
  - Assembly and operations
  - Information handling
  - Reliability
- Eventual goal: Large, high-performance products including manufacturing tools


Multiscan300sf
Trinitron
SONY

A desktop nanofactory manufactures a Filtomat M102C high performance self-cleaning water filter


Ridge joints interlock to connect nanoblocks


The product is extruded at a surface that assembles nanoblocks one layer at a time


A robot arm with thiophene-based molecular actuators adds a nanoblock to the extruded product

Outline

- Foundational approach
- Ultimate goal
- Existing capabilities
- Roadmap

Information Delivery

- Existing manufacturing technologies:

  A few KB per second

- Goal:

  A few GB per second

- This requires:
  - Very small tools

    (or massively parallel medium-small tools)
  - Reliable operations

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Rapid Design

- Once you get a set of reliable tools…
  You can combine them to make new tools
- Once you can build lots of variants…
  You can do evolutionary design
- With high performance and small parts…
  You can afford to use levels of abstraction

Planar Assembly

- ➔Scaling laws indicate that deposition speed is independent of block/robot size
- ➔Robots can be sub-micron size

  (Human cell = 20 micron)
- ➔Rapid joining should allow cm/sec deposition
- → Build large products directly from sub-micron blocks

(Build sub-micron blocks directly from atoms…)

Molecular fabrication

- Today: Bulk chemistry
- Environmentally controlled polymer fabrication
  - Sequence of operations
  - Light (“DNA Chip”)
- Goal: Mechanically controlled reactions
  - Sequence
  - Position

Mechanosynthesis: Just a Tool

- Can be either “solution phase” or “machine phase”
- Mechanical control of reactions: More a style than a restriction
- Control can be direct or indirect
- Implies precise nanoscale tools – which we want anyway

Error Handling in Generational Manufacturing

- In molecular devices, errors are digital
- Error rates vary by many orders of magnitude
- In small self-contained devices, you just need an error rate less than the number of operations
- In large devices, you will have errors
  - You need to work around them, not pass them on

Nanoscale Toolkit

- We want tools that are:
  - Reliable
  - Dependable
  - Easy to characterize
  - Very flexible
- Short-term tools

Actuators; Binding/recognition; Conductors; Sensors; Bonding; Structure

- Long-term tools

Digital logic; Bearings; Mechanosynthesis

The Ultimate Goal

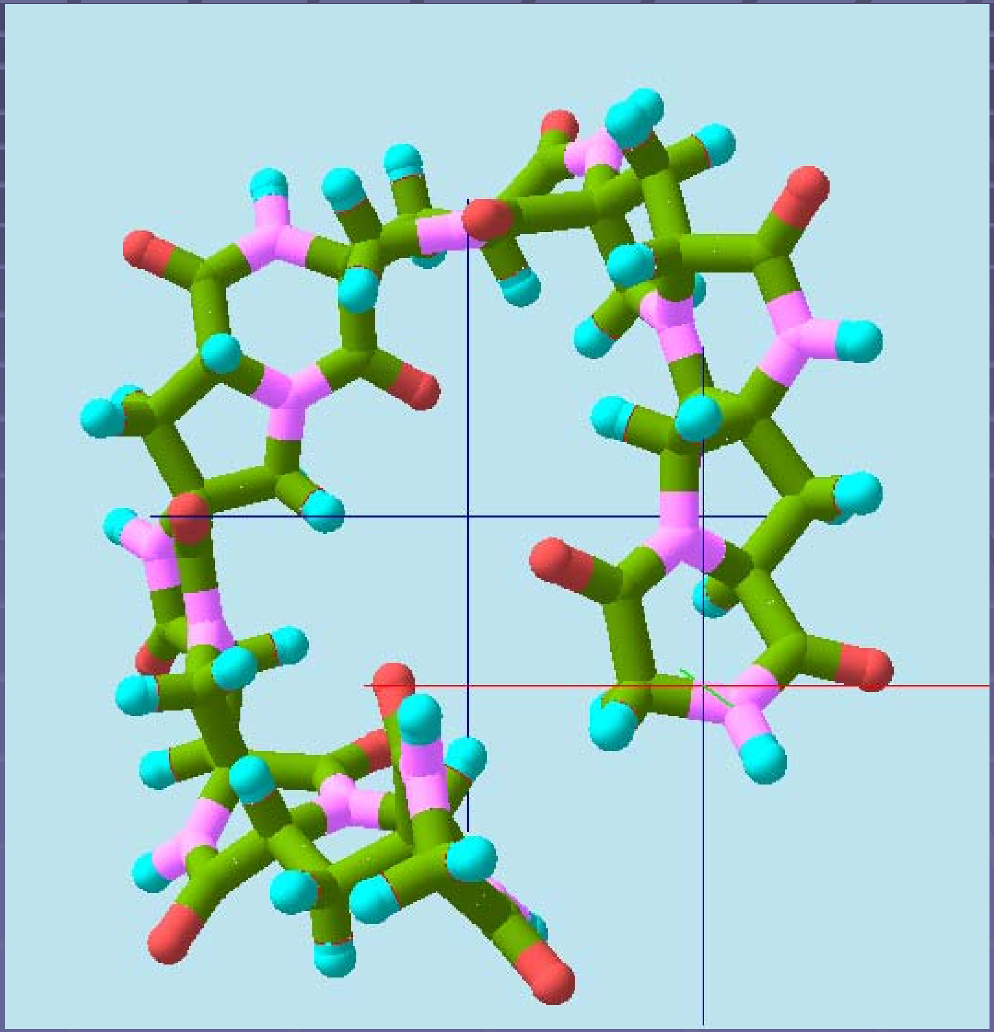
- Tabletop nanofactoy
  - Produces its own mass in ~1 hour
  - Uses simple feedstock
  - Direct computer control; Rapid prototyping
  - Powerful nanoscale toolkit
  - Very high performance products
  - Easy product design
- Burch/Drexler animation (with real chemistry)

Where To Start

- Simple 2D array of block-placing equipment
- A “membrane” separating loose blocks from product
- Selective placement of blocks, optionally followed by strengthening connections
- Blocks (5-20 nm?) are pre-made
  - Chemistry
  - Self assembly
  - Templating, mechanosynthesis

Building blocks

- DNA
- RNA
- Protein
- Schafmeister's polymers
- Other…



Binding and Bonding

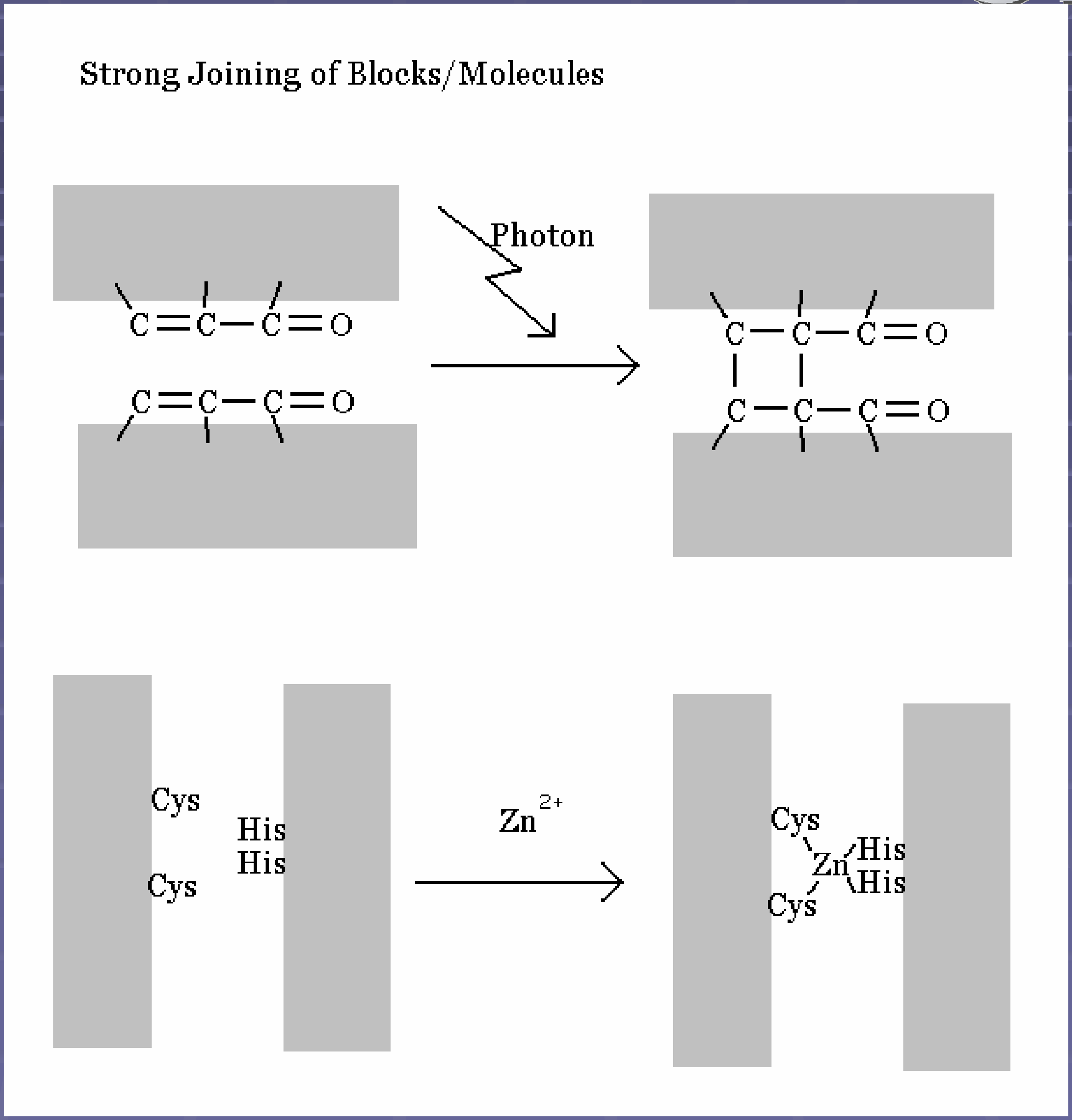
- Covalent
- Metal ligation
- Dative

- Hydrogen
- Charge/Dipole

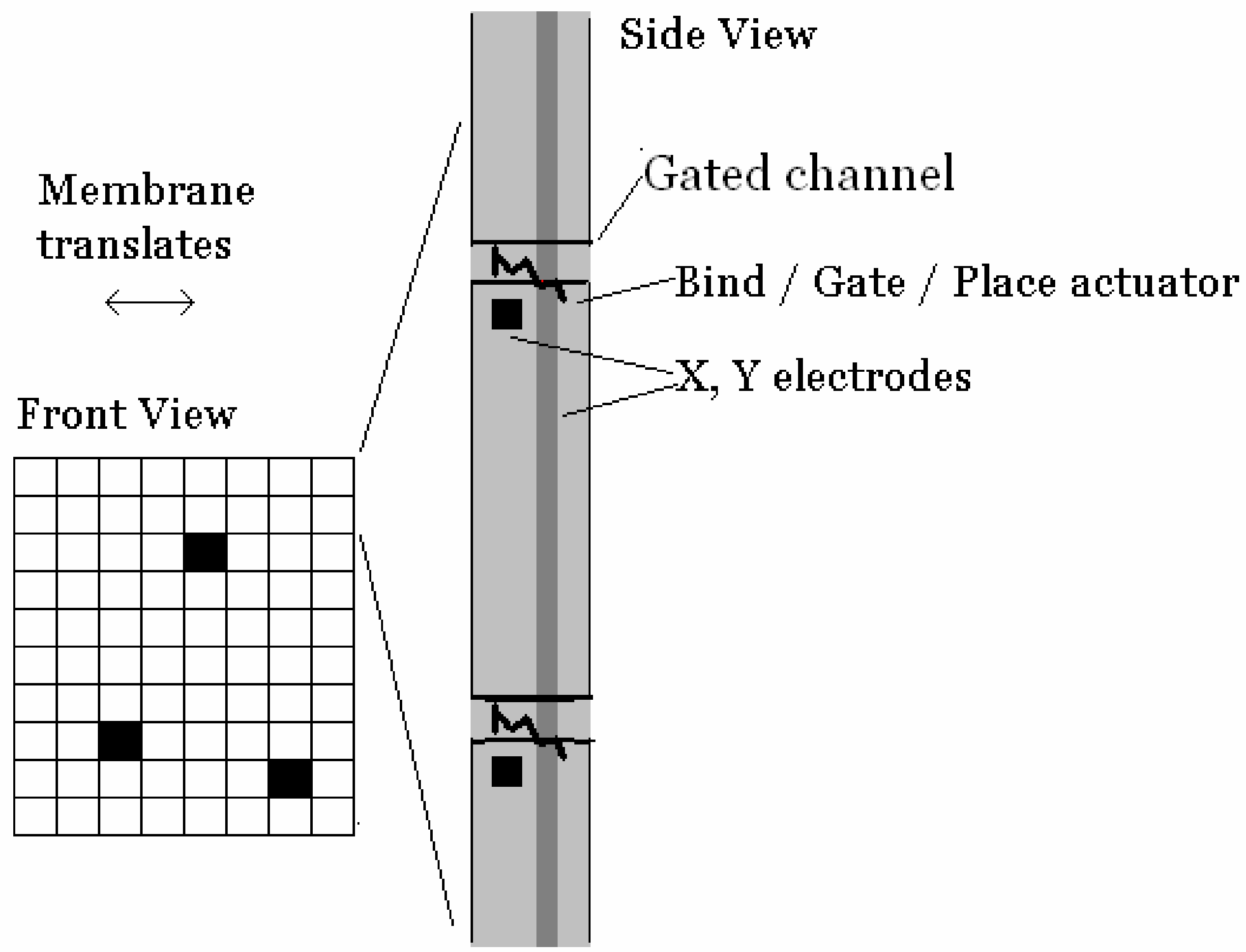
- Van der Waals ("surface forces")

Bonding Blocks

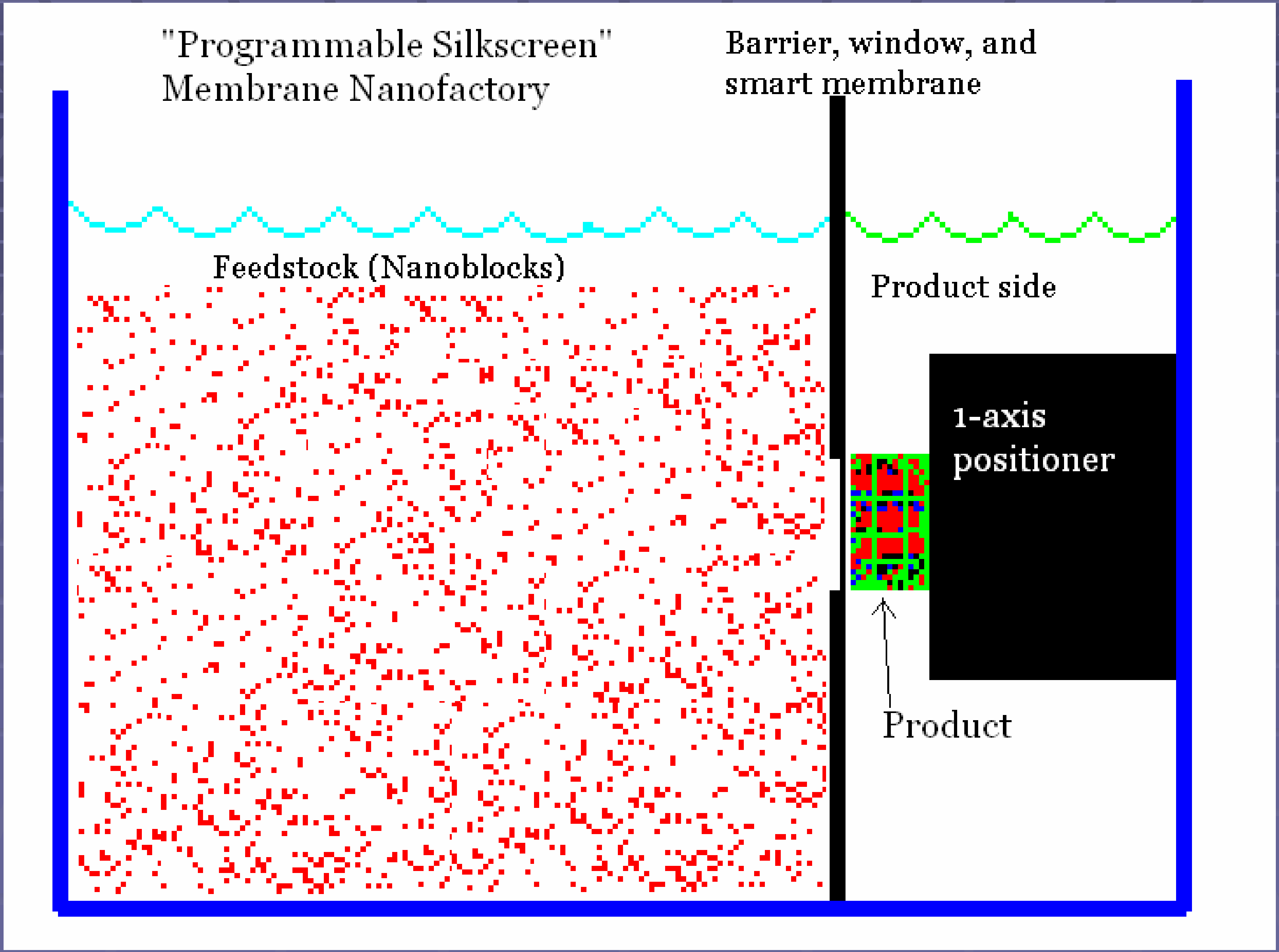
- By light
- By zinc
- Other…



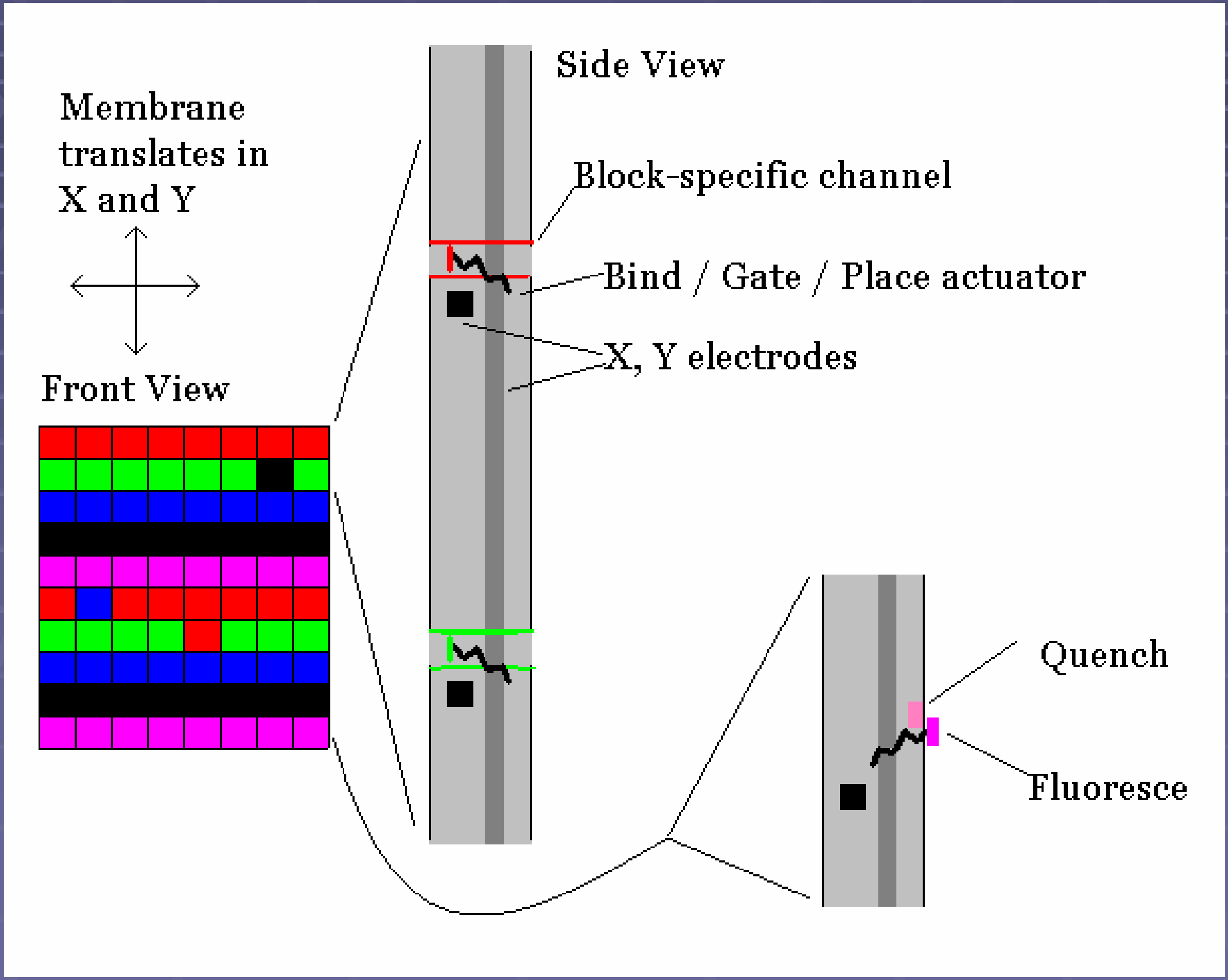
Smart Silkscreen



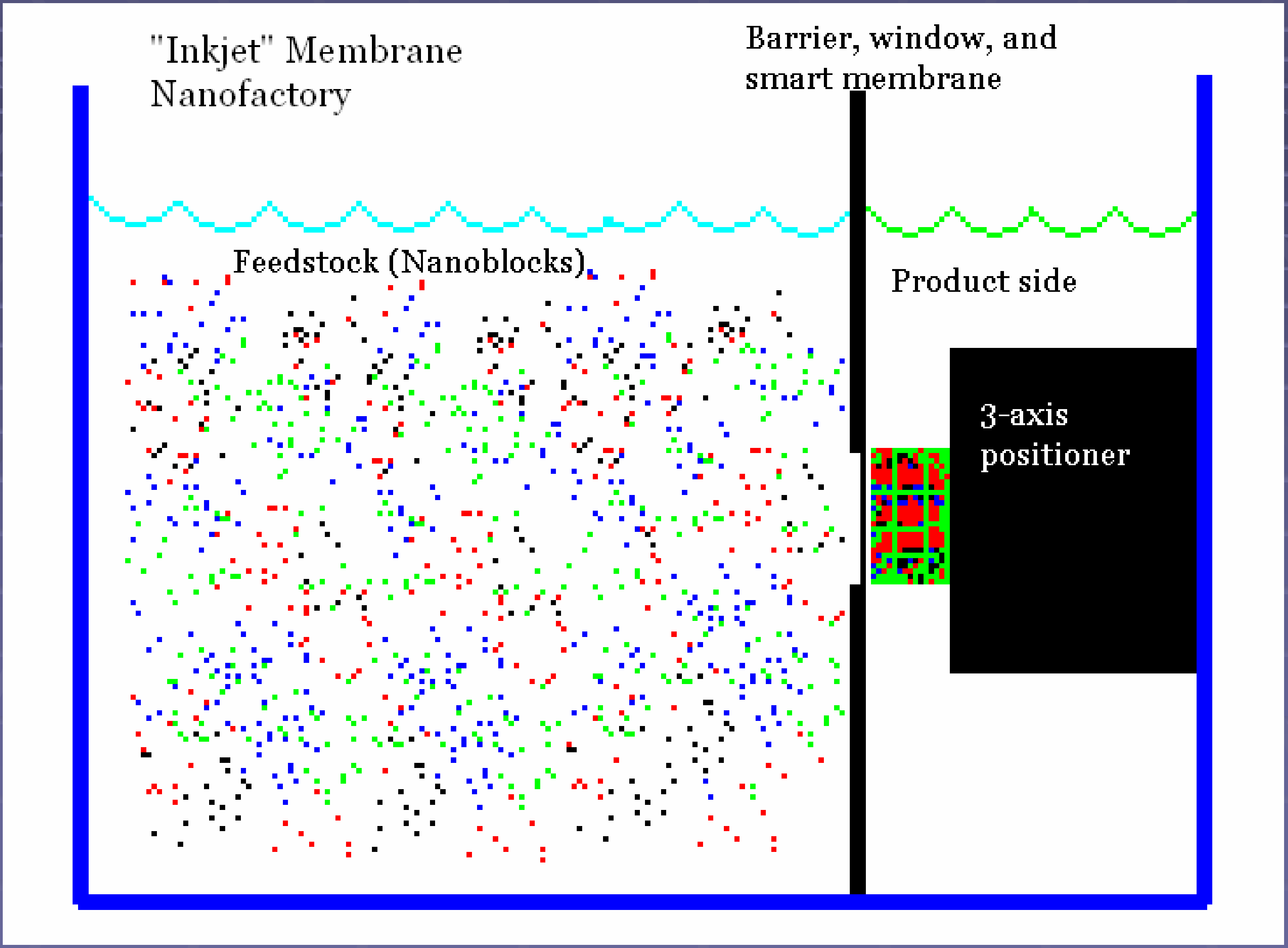
Simplest Nanofactory



First Improvement



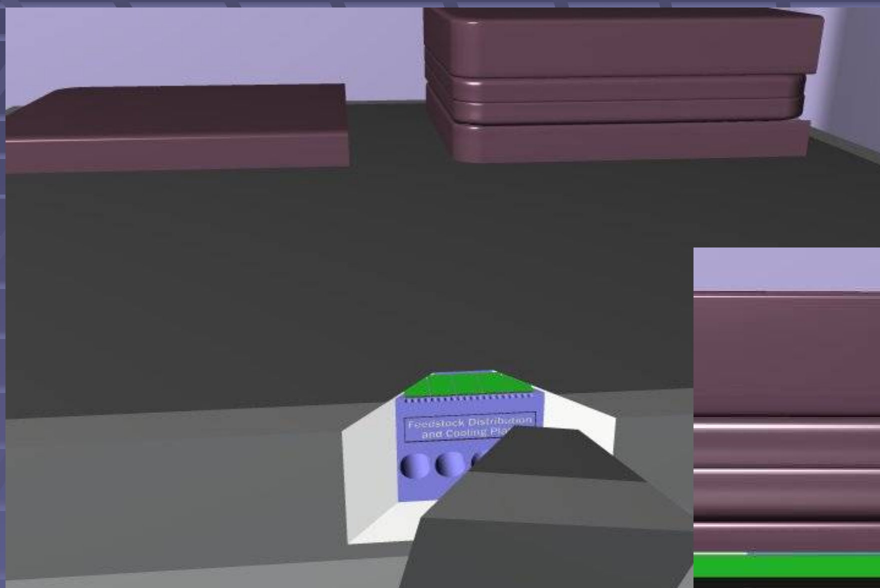
Improved nanofactory

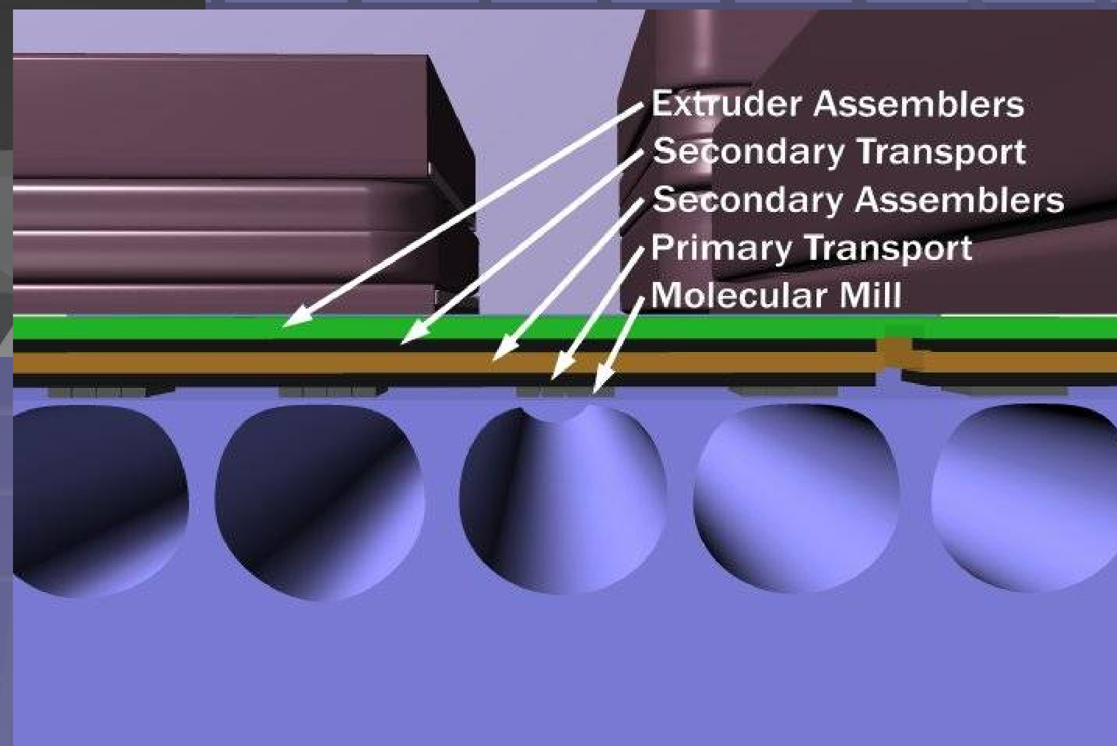


Roadmap

- Silkscreen membrane
- Inkjet membrane
- Add local digital logic
- Improve error handling
- Improve the mechanicals
- Add intermediate block-assembly stages
- Add mechanosynthesis
- Add directed internal transport
- Remove solvent
- Add mill-style synthesis

Goal…





- John Burch, Lizard Fire Studios

Local digital logic

- HP’s “crossbar” claims storage, amplification, logic
- Mechanical logic? Nanoscale machines move at GHz speeds…

Improve error handling

- With primitive membrane and small area, you can handle errors from the top
- With internal function, you need redundancy
- Local error handling reduces data flow
  - Especially the difficult back-channel

Improve the mechanicals

- Actuators
  - DNA (tweezers, rotary motors)
  - ATP (ATP synthase, kinesin, etc.)
  - Ion (linear rotaxane dimers, contractile polymers)
  - Redox (rotaxane, VPL, etc.)
  - Photo or electrochemical (pseudorotaxanes)
  - Electrostatic
- Bearings
  - Single bond
  - Compliant (squishy)
  - Superlubricity

Intermediate block assembly

- Combine molecules into blocks
- Improve throughput
- Enhance flexibility
- Add “fins” or other structure on the feedstock side to supply the assembly plane

Mechanosynthesis

- Simpler, cheaper feedstock
- Smaller, less error-prone feedstock intake
- Wider range of components
- Low level programmability (faster R&D)
- Smaller features?
- Higher bond density?

Directed internal transport

- Shuffle product components within the factory
- Specialization and optimization of factory equipment
- Efficient handling of product voids
- Efficient handling of errors (redundancy)

Remove solvent

- Less drag; more throughput; higher efficiency
- Feedstock can still be delivered in solution
- Limits choice of actuators
- May require different synthetic reactions
- This may be a good thing!
  - Better materials
  - More extreme reactions

Mill-style synthesis

- Less flexible but a lot faster than robot-style synthesis
- Easier to recover reaction energy (stiffer equipment, smoother motion)
- Less computation per operation

- Less beneficial for component assembly, but may still be useful

Conclusion

- Today: We can build and join precise molecular parts.
- With this NIAC project, we have begun design of a system that can do precise, programmed, actuated assembly of molecular parts.
- From there, incremental steps lead to desktop nanofactory.

Who we are

- Center for Responsible Nanotechnology:

  Research and education on advanced nanotech capabilities and implications
- Researchers:
  - Chris Phoenix, CRN Director of Research

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  - Tihamer Toth-Fejel