Thermodynamically Favoured DNA Computing and Storage: Robust, Programmable, Scalable, Fast, and Renewable

Abeer Eshra

Storage and Computing with DNA 2025

Sorbonne Université, Paris, 21/06/2025

Maynooth University
National University of Ireland Maynooth

Hamilton Institute

program
Major Groove

We are hiring!

Disco
DNA Infrastructure for Storage and COmputation

European Innovation Council

Funded by the European Union

tilibit nanosystems

Thermodynamically favoured computation

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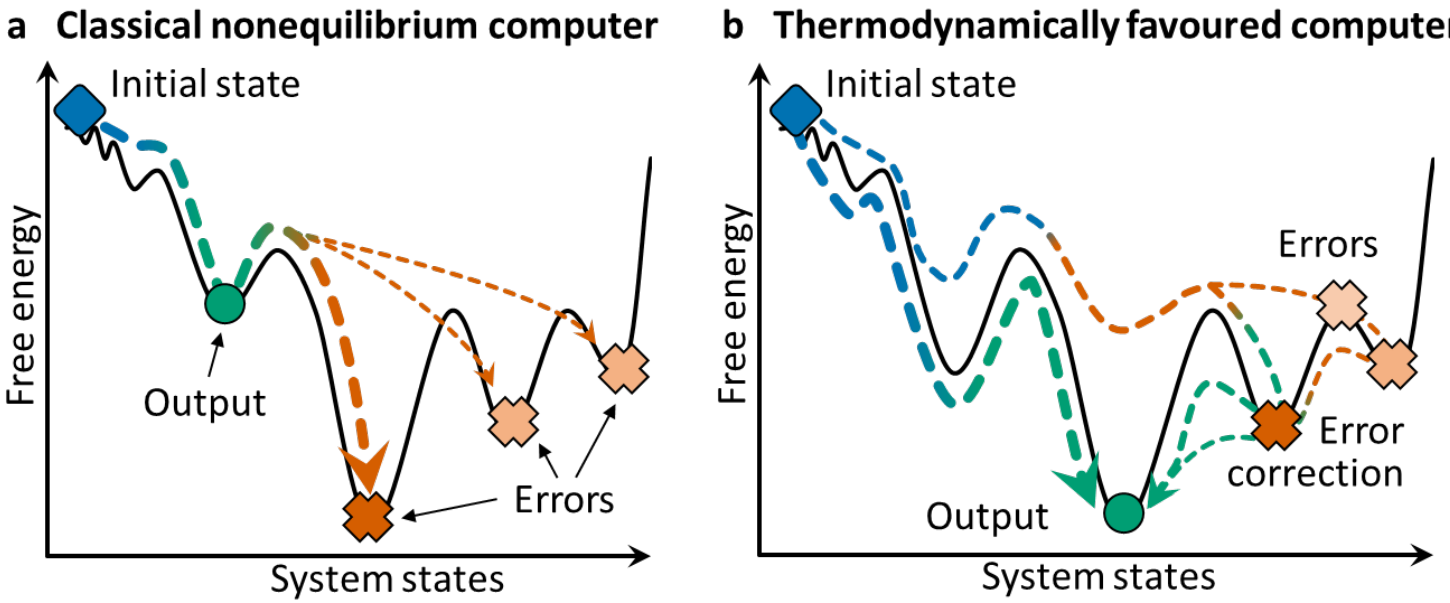
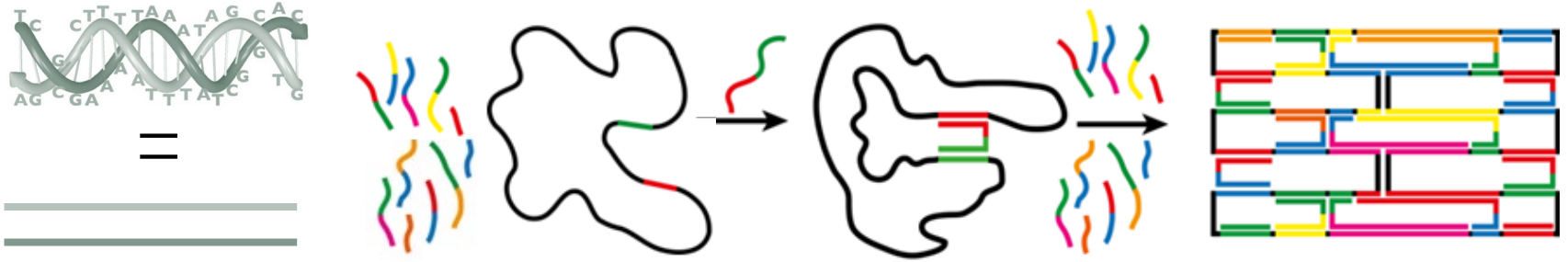
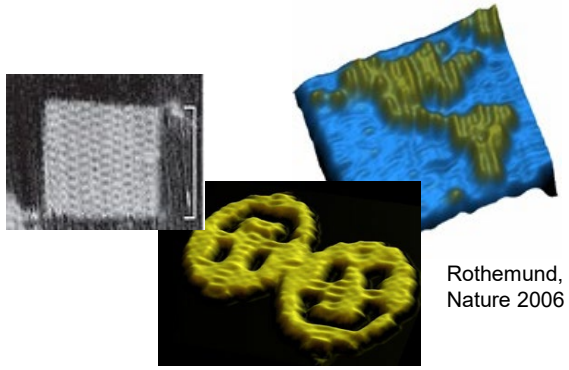


Animation: S Douglas

A Thermodynamically Favoured Molecular Computer: Robust, Fast, Renewable, Scalable
Tristan Stérin*, Abeer Eshra*, Janet Adio, Constantine Glen Evans and Damien Woods
*Equal contribution, Under review.

DNA Origami





Rothemund, Nature 2006

Scaffolded DNA Computer: tile-based model

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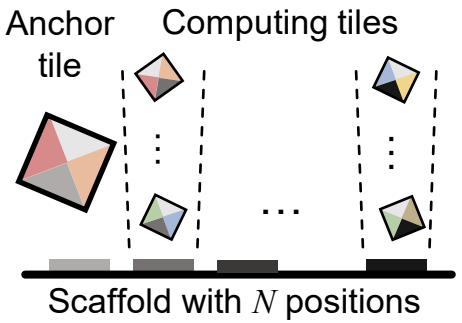
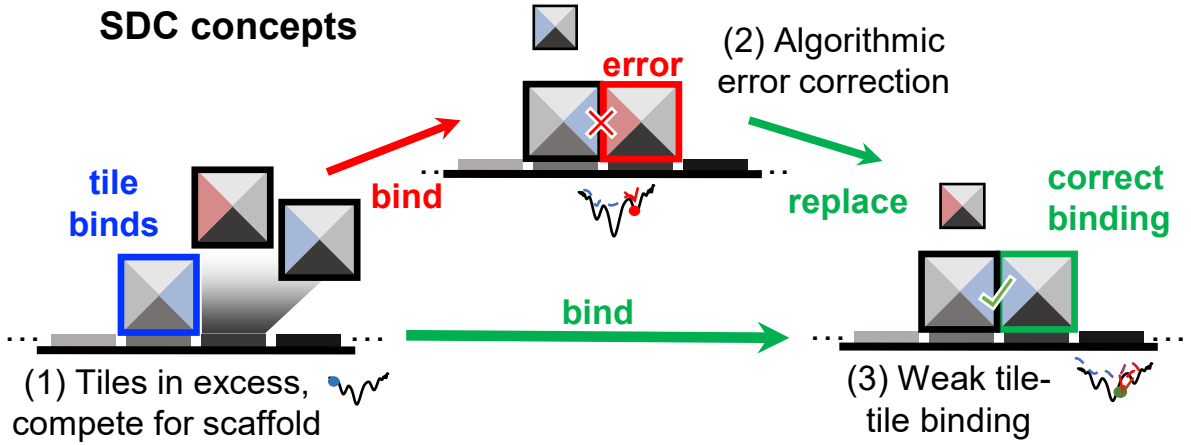
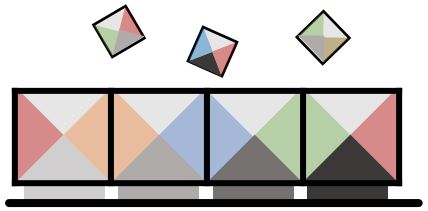
SDC instance



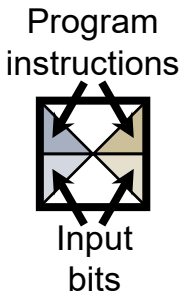
SDC concepts



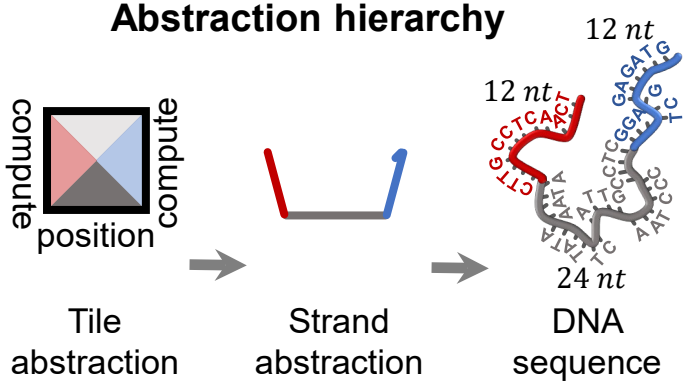
Thermodynamically favoured output



Encoding



Abstraction hierarchy



Strand-domain implementation

Scaffolded DNA Computer: BitCopy

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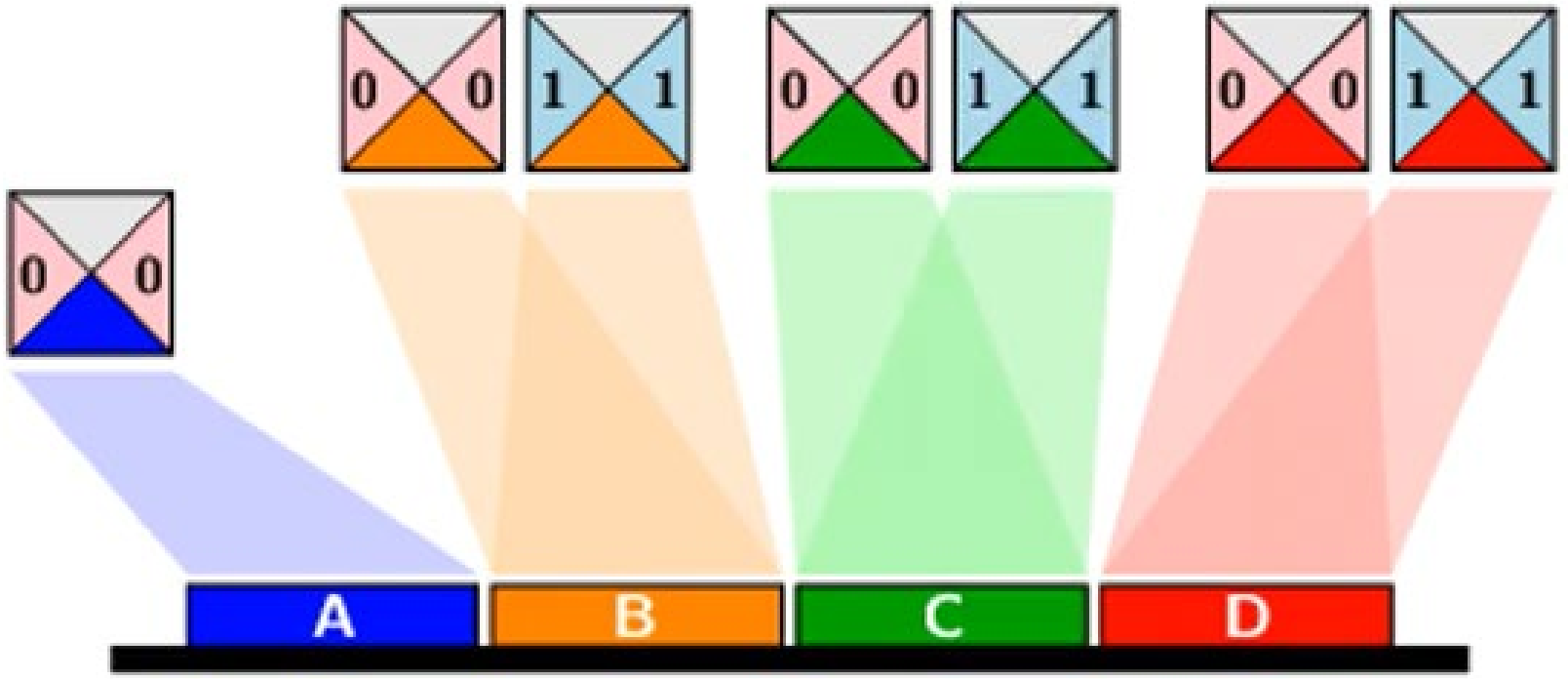

Programming a Scaffolded DNA Computer

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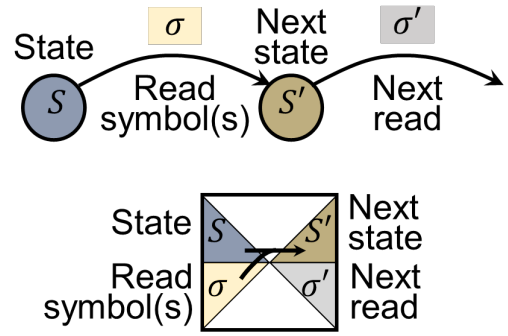
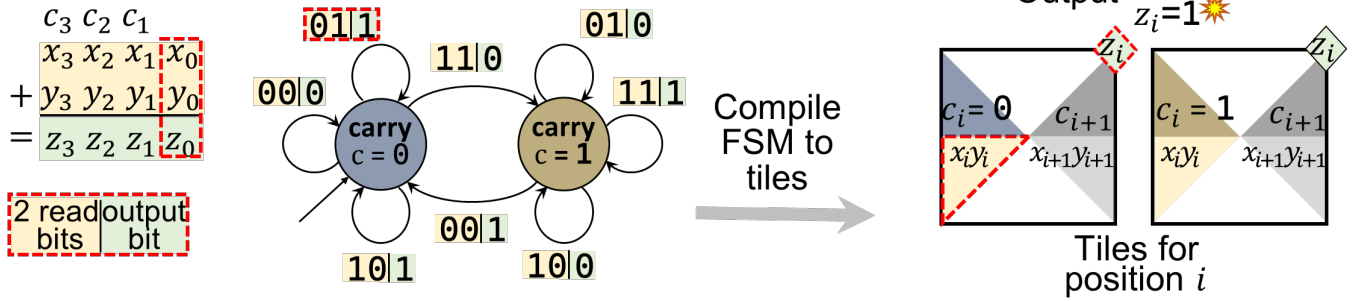
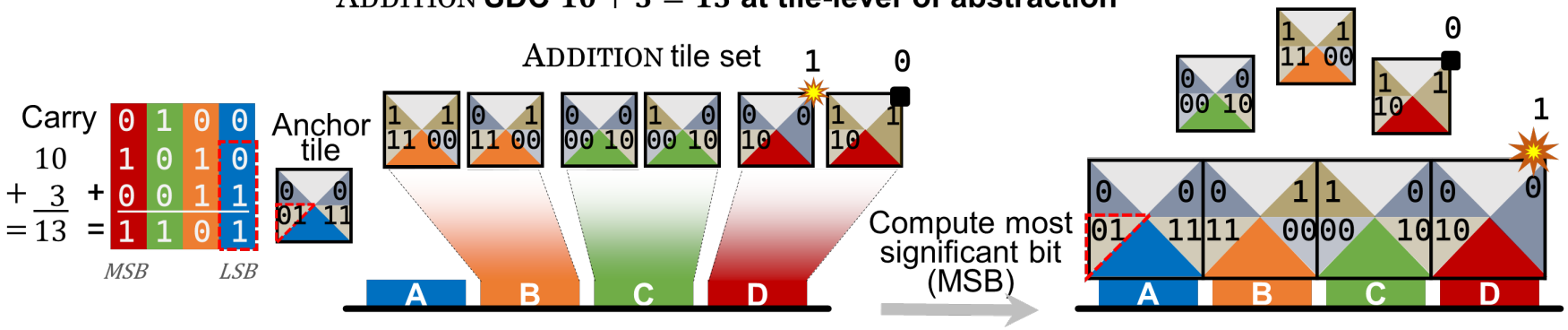
General FSM to SDC scheme



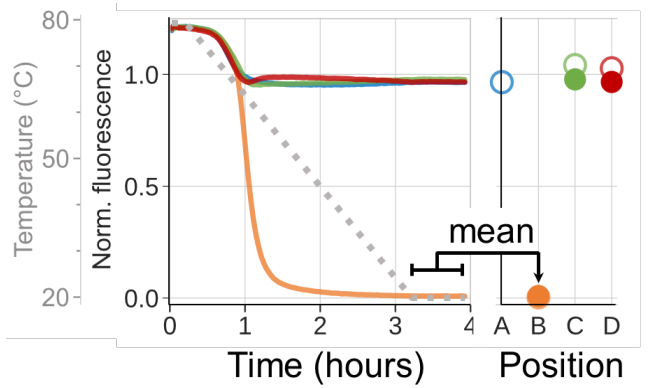
$x + y = z$: FSM complied to 4-bit ADDITION SDC

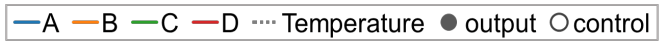


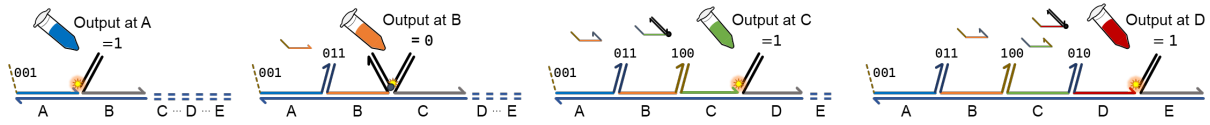
ADDITION SDC $10 + 3 = 13$ at tile-level of abstraction



Experimental results: $10 + 3 = 13 = 1101_2$







Programmable SDC

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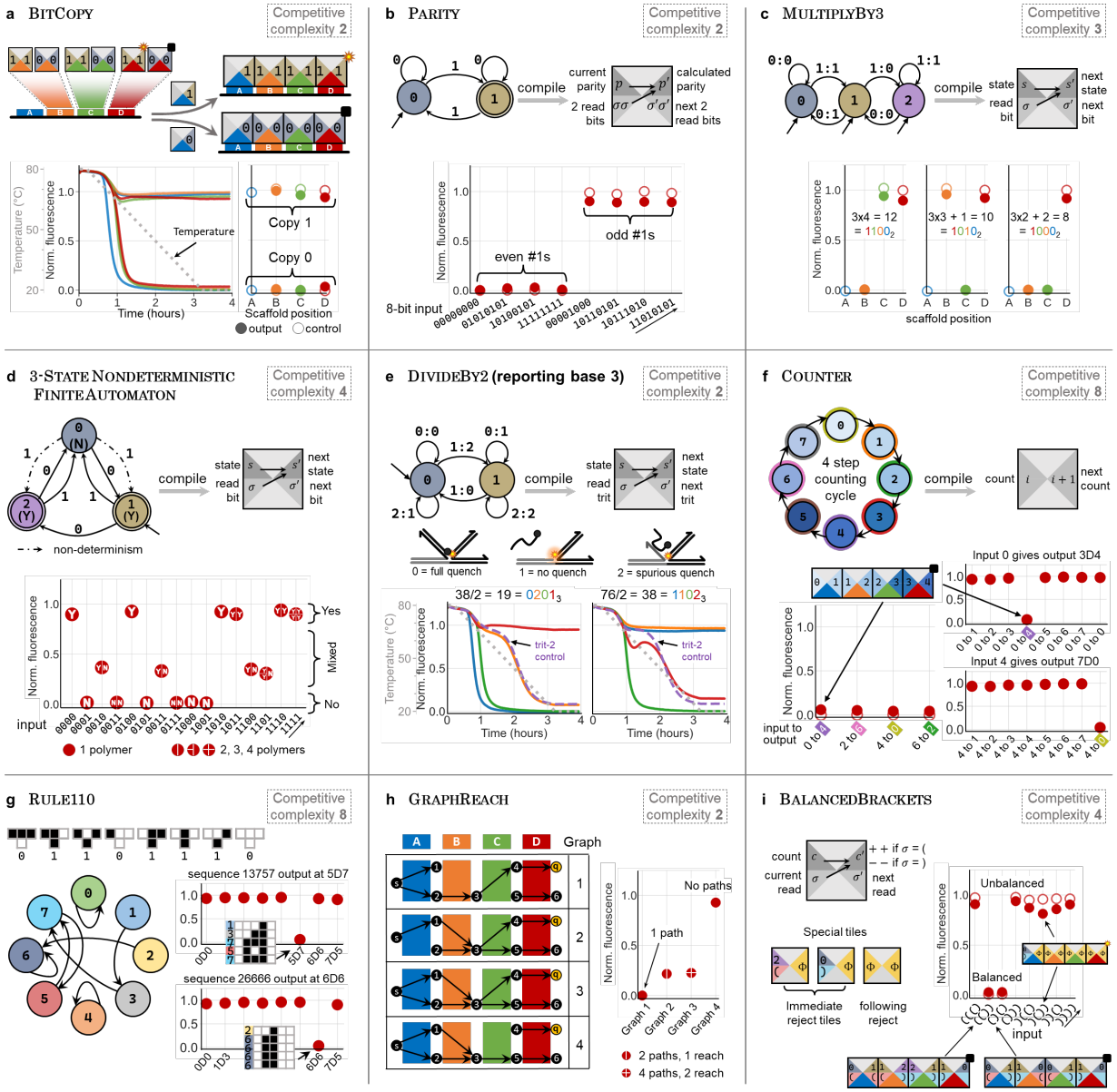
Implemented Programs

ADDITION	BALANCEDBRACKETS
PARITY	3-STATENFA
BITCOPY	RULE110
MULTIPLYBY3	GRAPHREACH
DIVIDEBY2	COUNTER



Speeding-up Scaffolded DNA Computer

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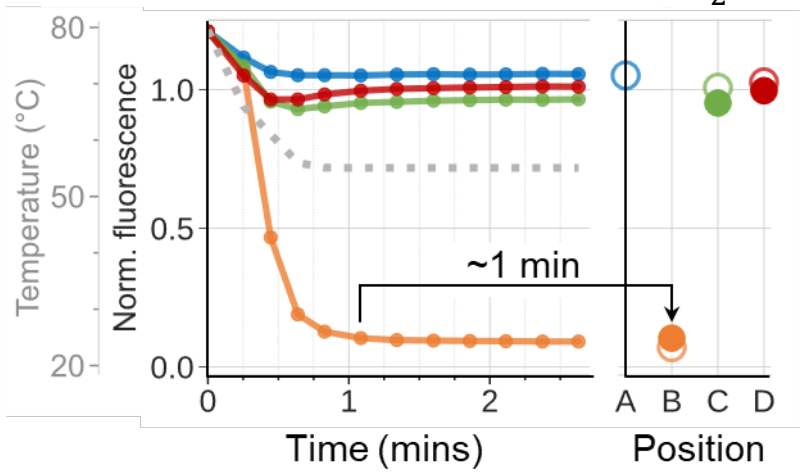
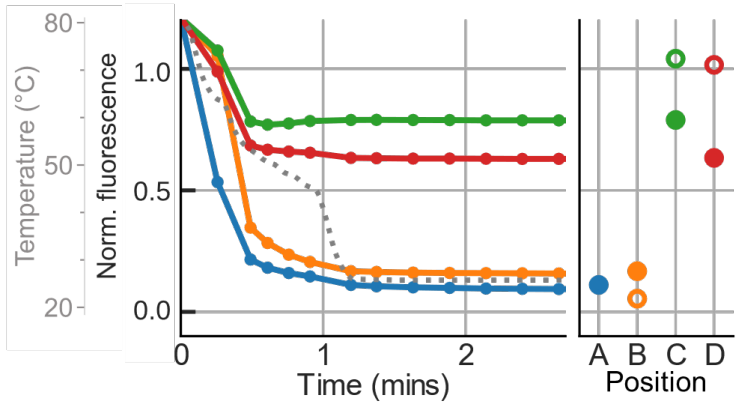
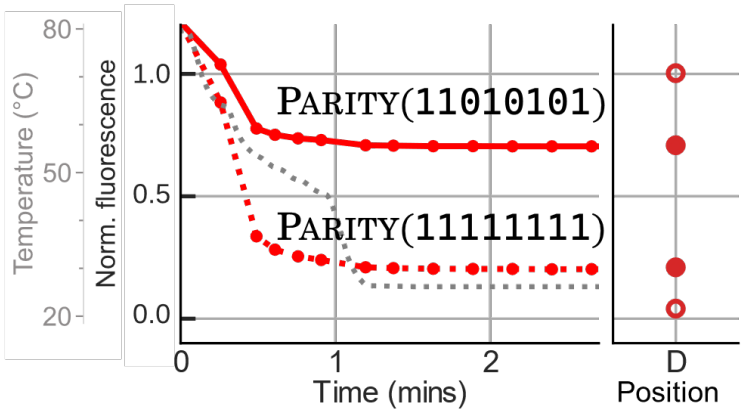
ADDITION: $10 + 3 = 13 = 1101_2$



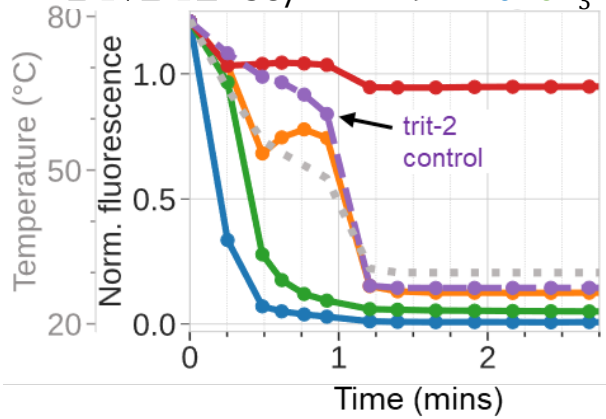
MULTIPLYBY3 : $3 \times 4 = 12 = 1100_2$



PARITY



DIVBY2: $38/2 = 19 = 0201_3$



A B C D Temperature output control

Renewable ♻ SDC

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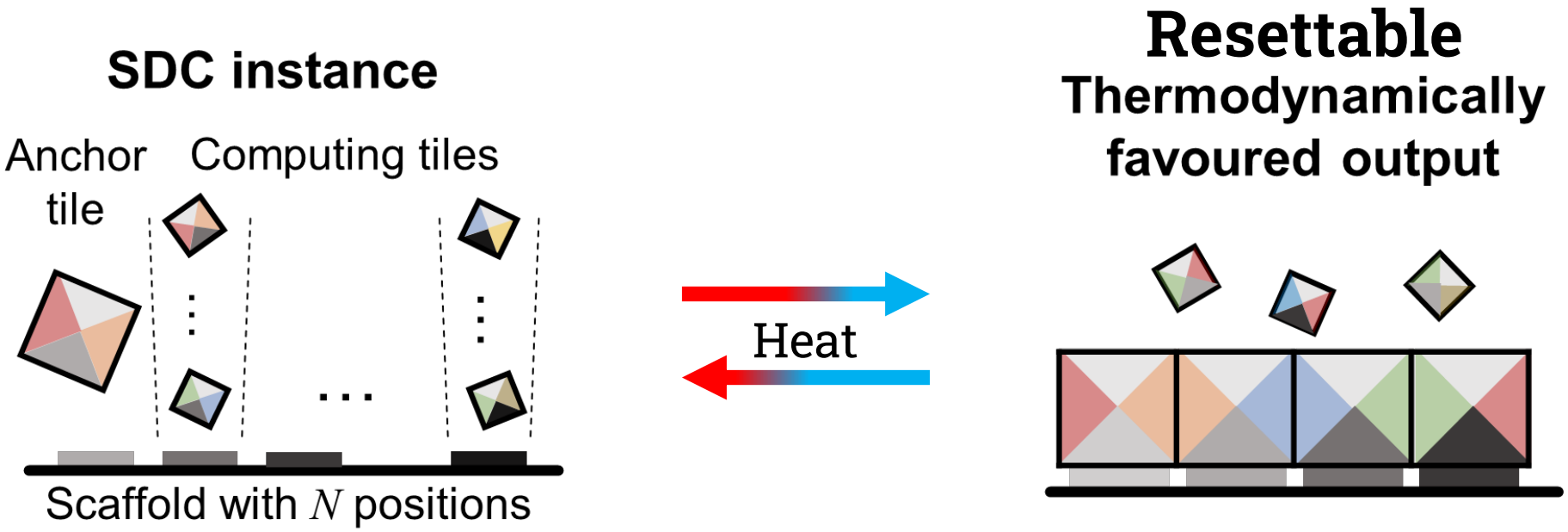
- Leveraging SDC principles to demonstrate renewability



Renewable ♻ SDC

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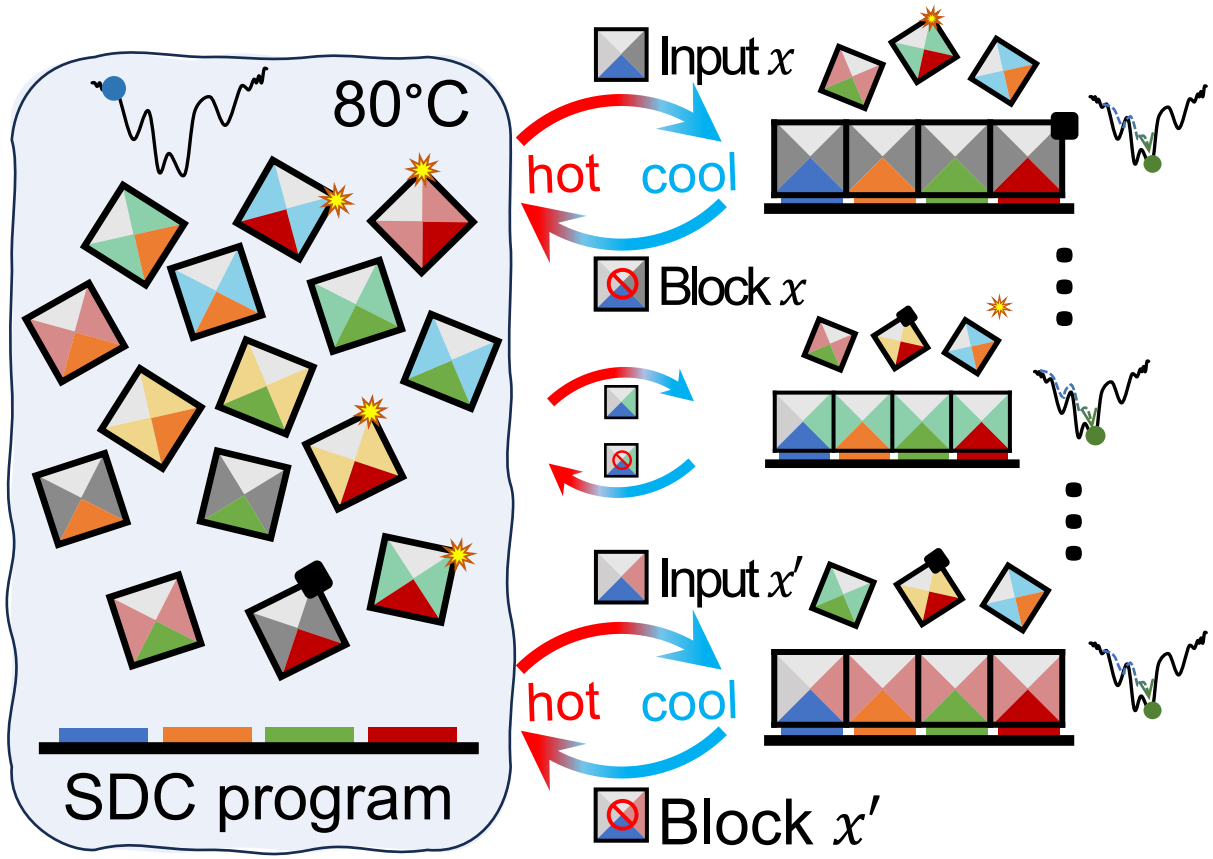

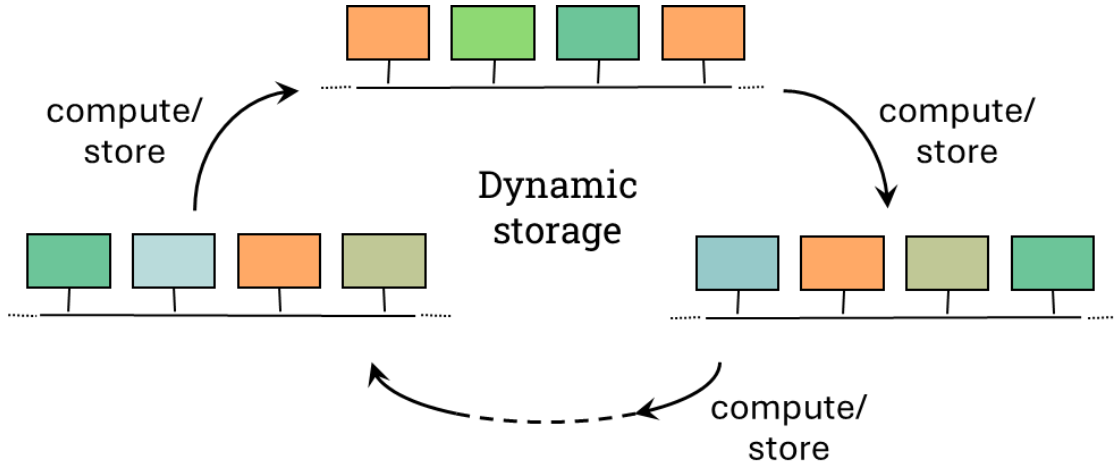

Renewable BitCopy Program

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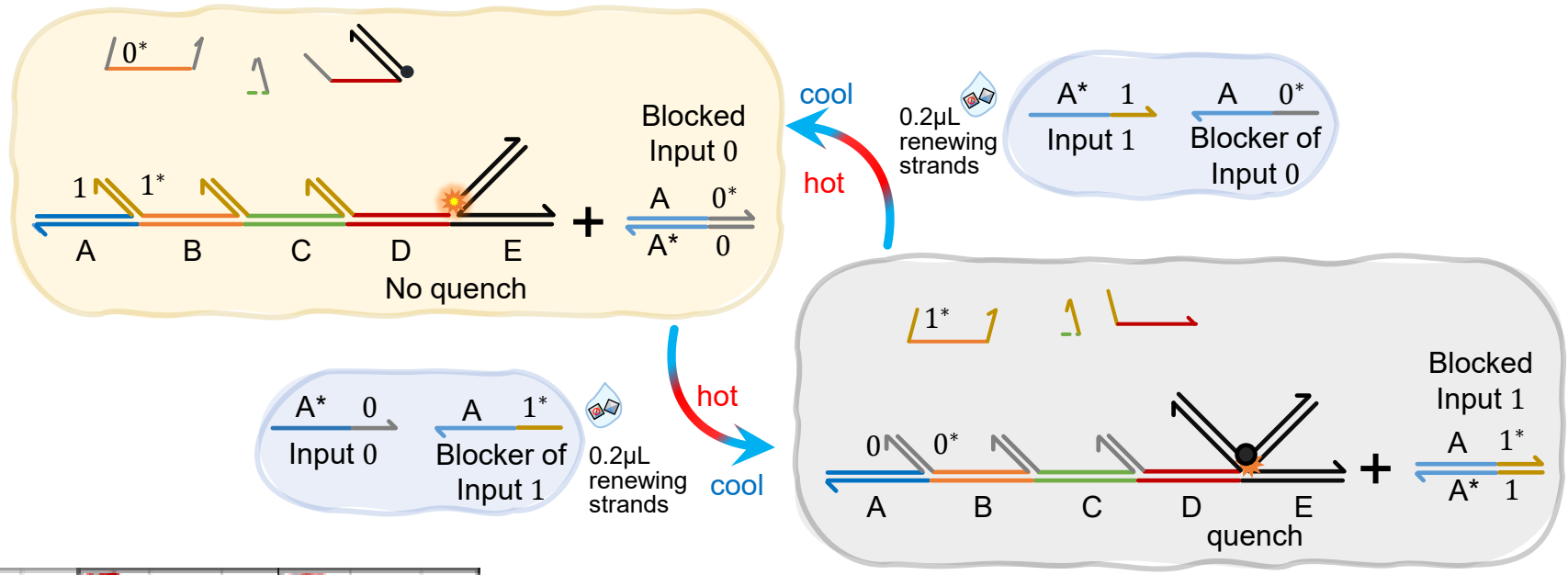

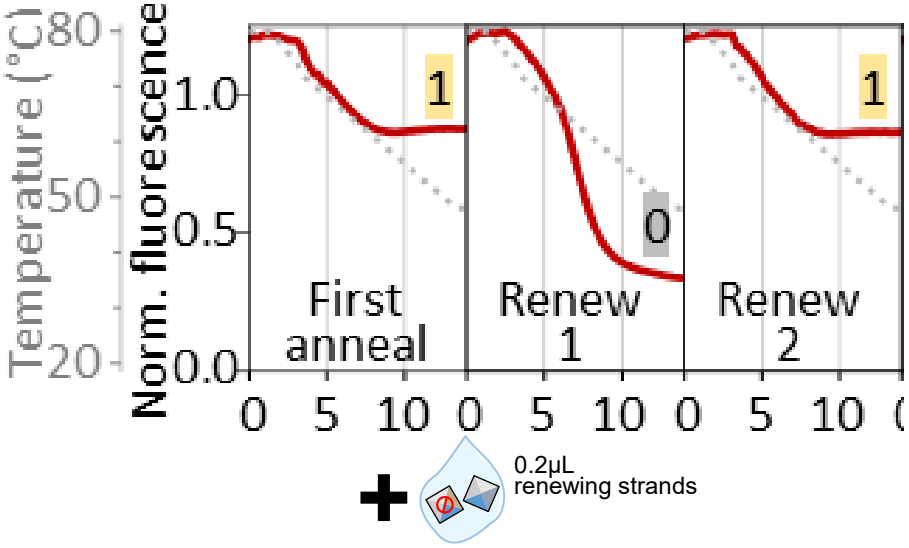

Renewable BitCopy Program

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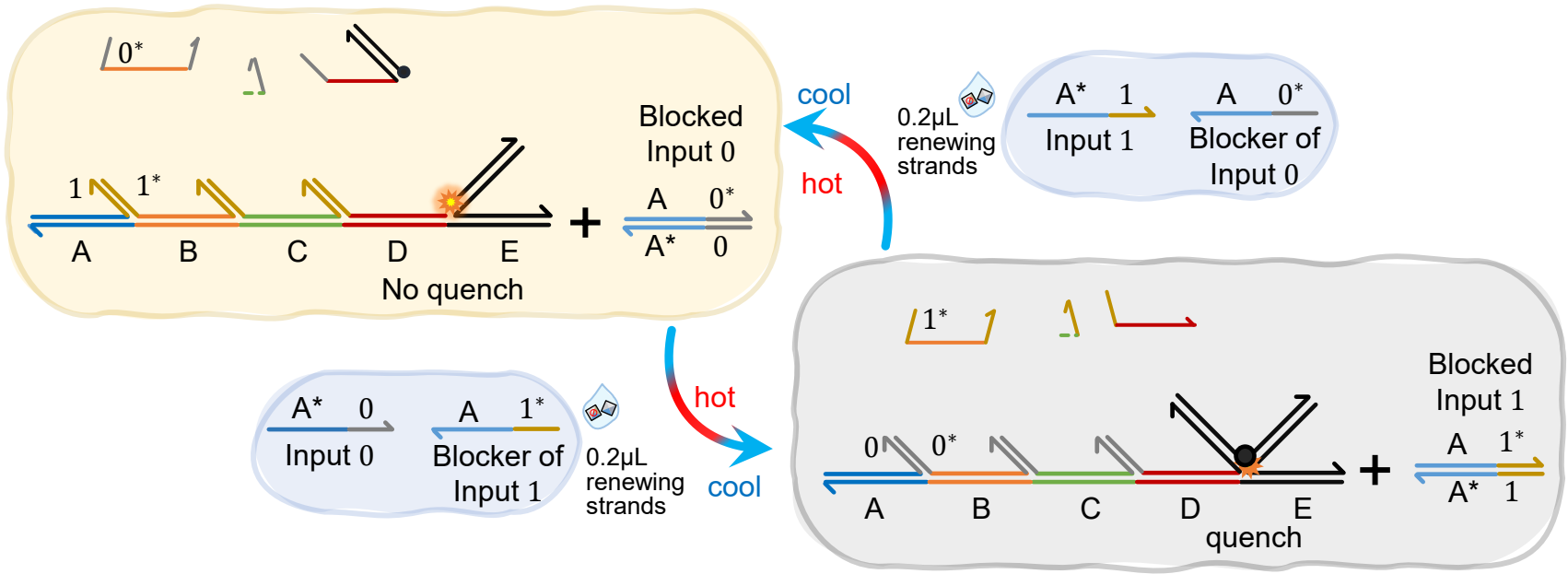

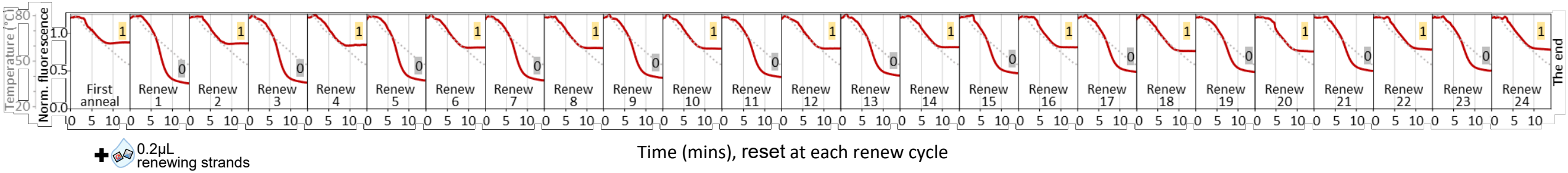

+ 0.2µL renewing strands

Renewable ADDITION program

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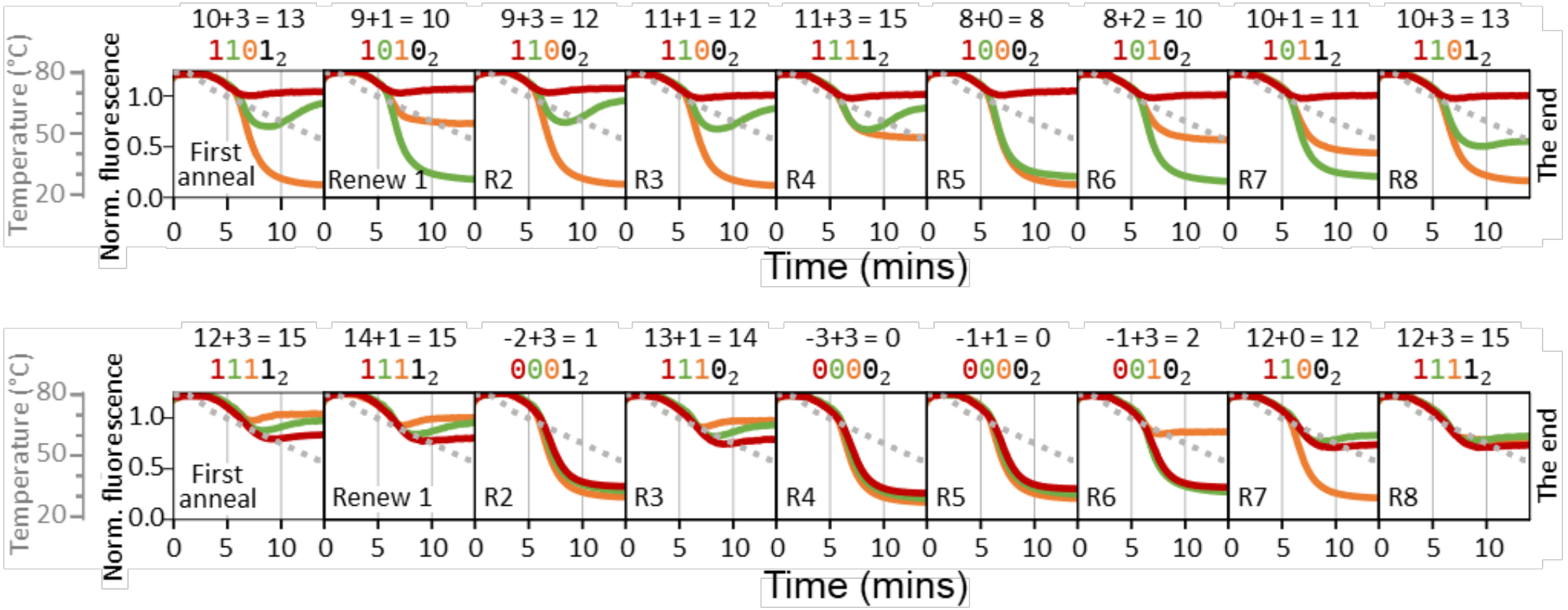
Two ADDITION programs, each renewed 8 times



Renewable COUNTER program

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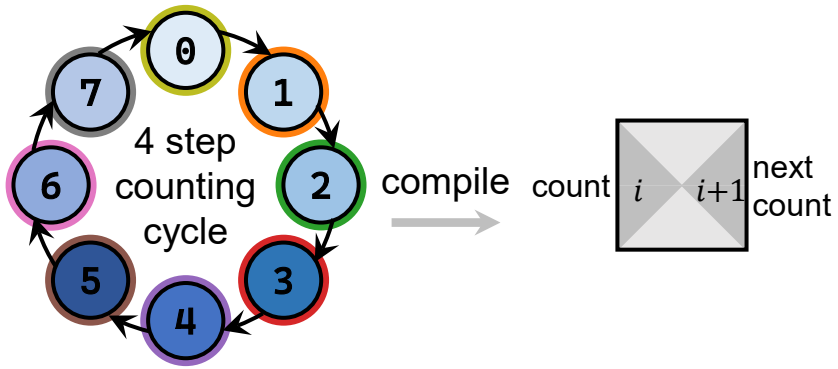
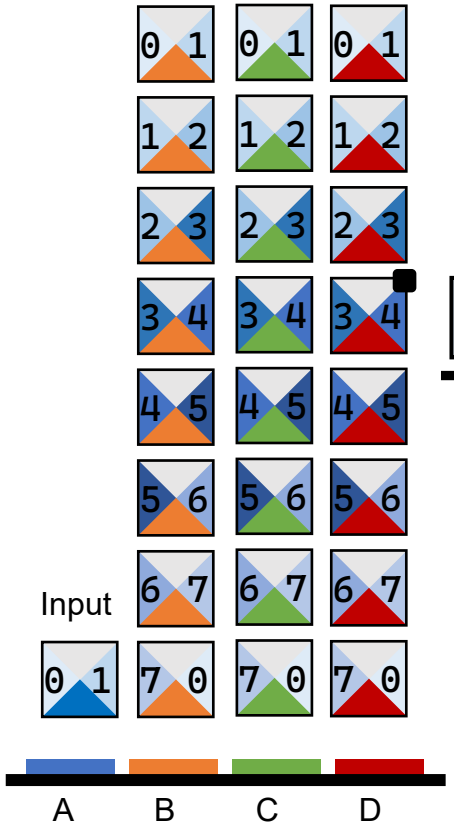
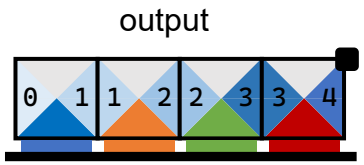
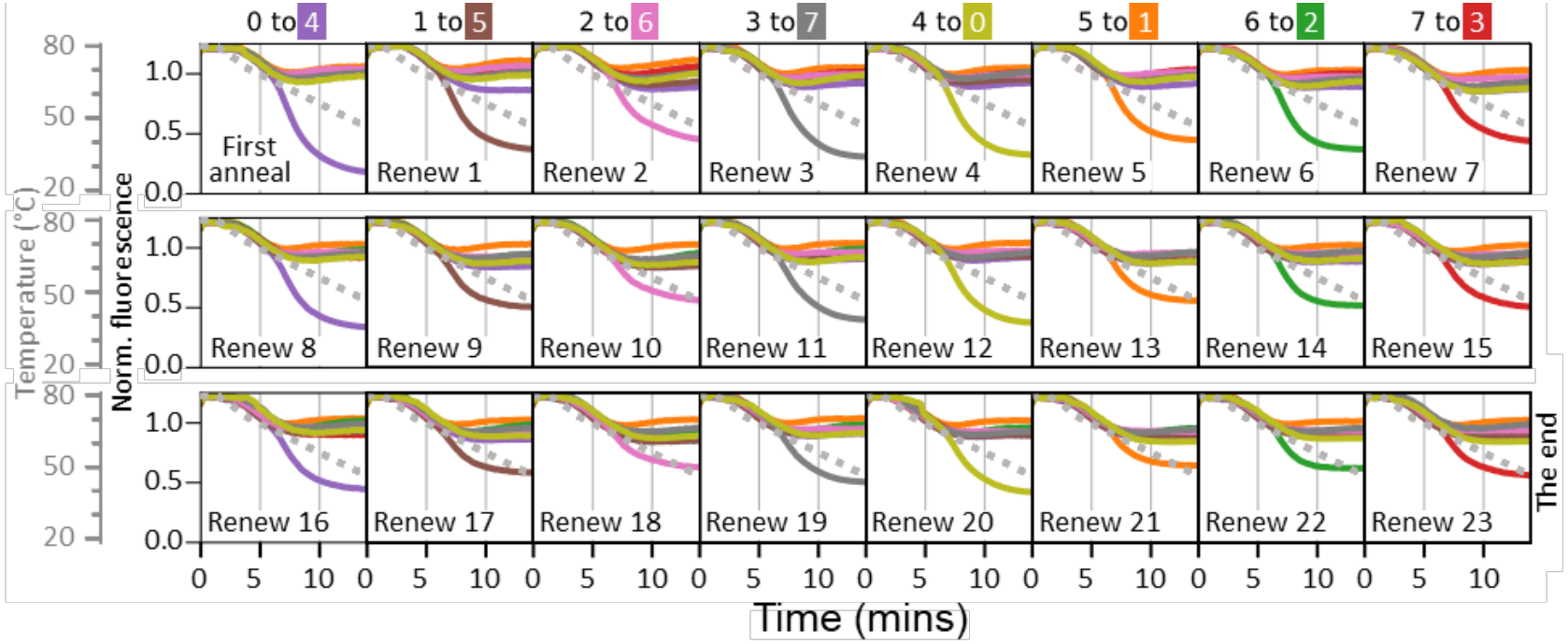






If quencher ■ is placed on any tile other than 3D4, the output signal will be “no-quench”

COUNTER program renewed 23 times (counts to input + 4, mod 8)



Scaling-up SDC: length 25 ADDITION

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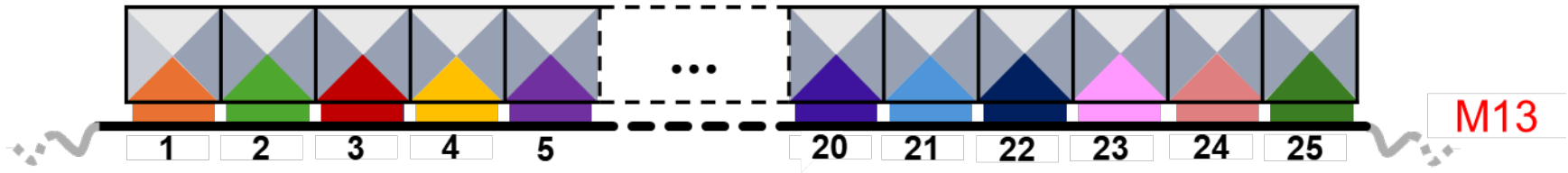
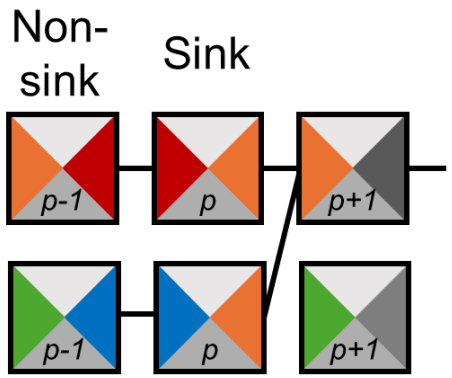
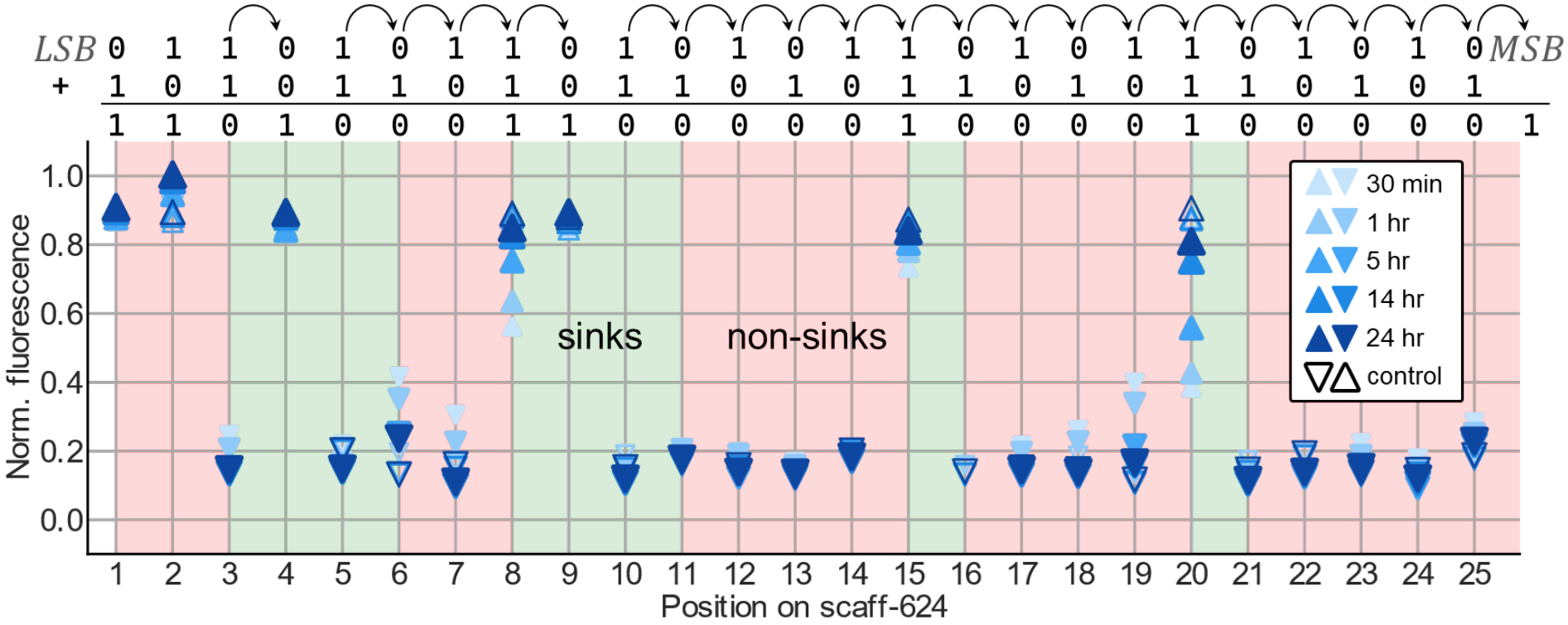
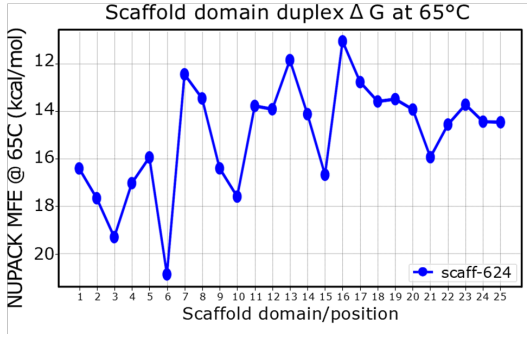
$$
\begin{aligned}
&11{,}365{,}078\\
+\;&22{,}730{,}421\\
=\;&34{,}095{,}499
\end{aligned}
$$







Length 25 scaffold energetics



Scaling-up SDC: len 25 ISOENERGETICBITCOPY

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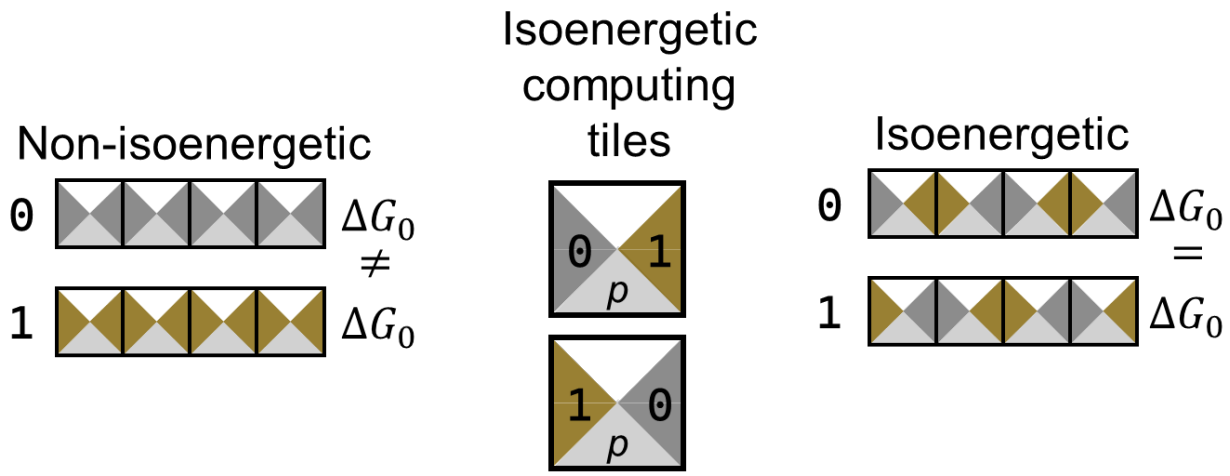
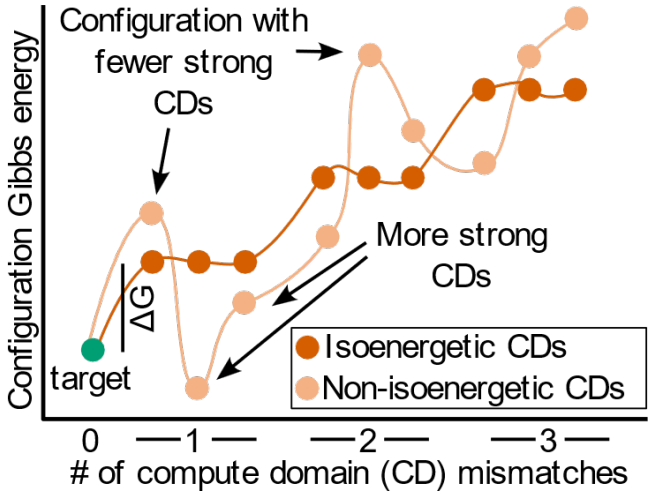
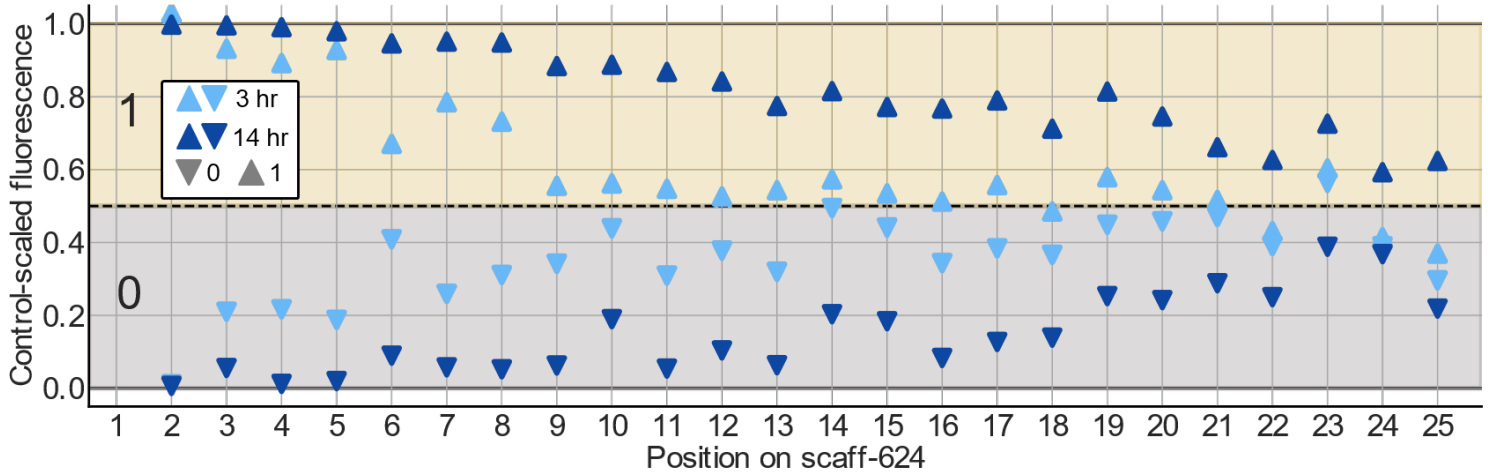




Length 25 ISOENERGETICBITCOPY



Scaffolded DNA Computer

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- **A Thermodynamically Favoured Molecular Computer is**
  - **Robust**
    - No special anneal or conditions
    - Ran very well after 1.5 years lying in the fridge
  - **Programmable**
    - Demonstrated with 10 different programs with different properties
  - **Fast**
    - 1 min for ~10-bit; 0.5–1 day for n = 25 ~75-bit
  - **Renewable**
    - Ran 25 times, additive complexity
  - **Scalable**
    - In practice (n <= 25)
    - In theory O(log n) domain length for scaffold length n
- **Next:**
  - Further **scaling up** to 1kb storage
  - **Automating** the renewal process
  - **Random access** in **rewritable** DNA storage using DISCO.
  - High throughput **read-out**
  - Extend SDC to **2D** computation, accommodating other computing classes

Acknowledgements and Join Us!

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prgm

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Taighde Éireann Research Ireland

Open positions: PhDs & Postdocs – Join us!

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Tristan Stérin
Constantine Evans
Cai Woods
Ahmed Shalaby
Janet Adio
Angel Cervera Roldan
Kim Reilly

Maynooth University
National University of Ireland Maynooth

Hamilton Institute