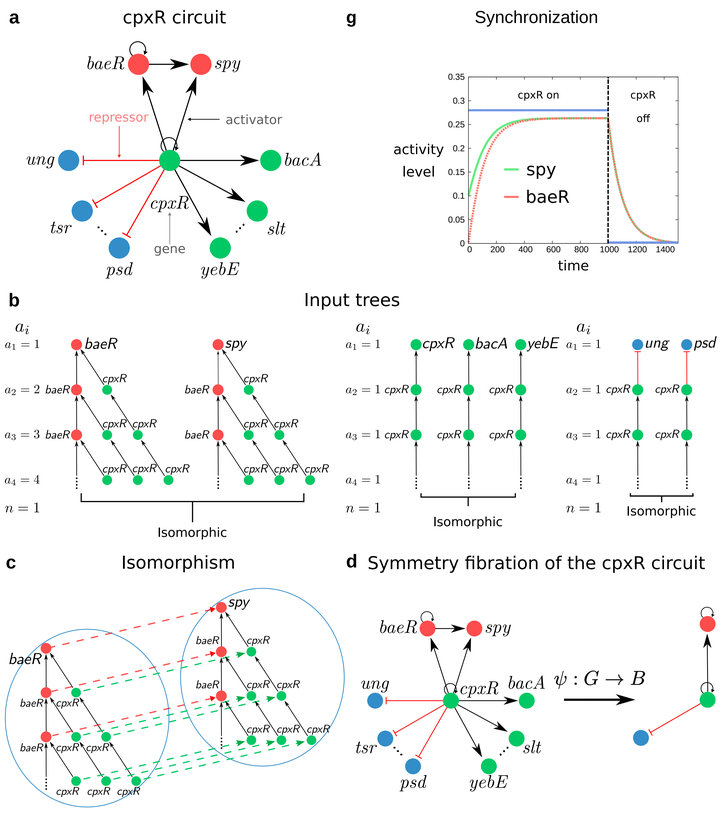
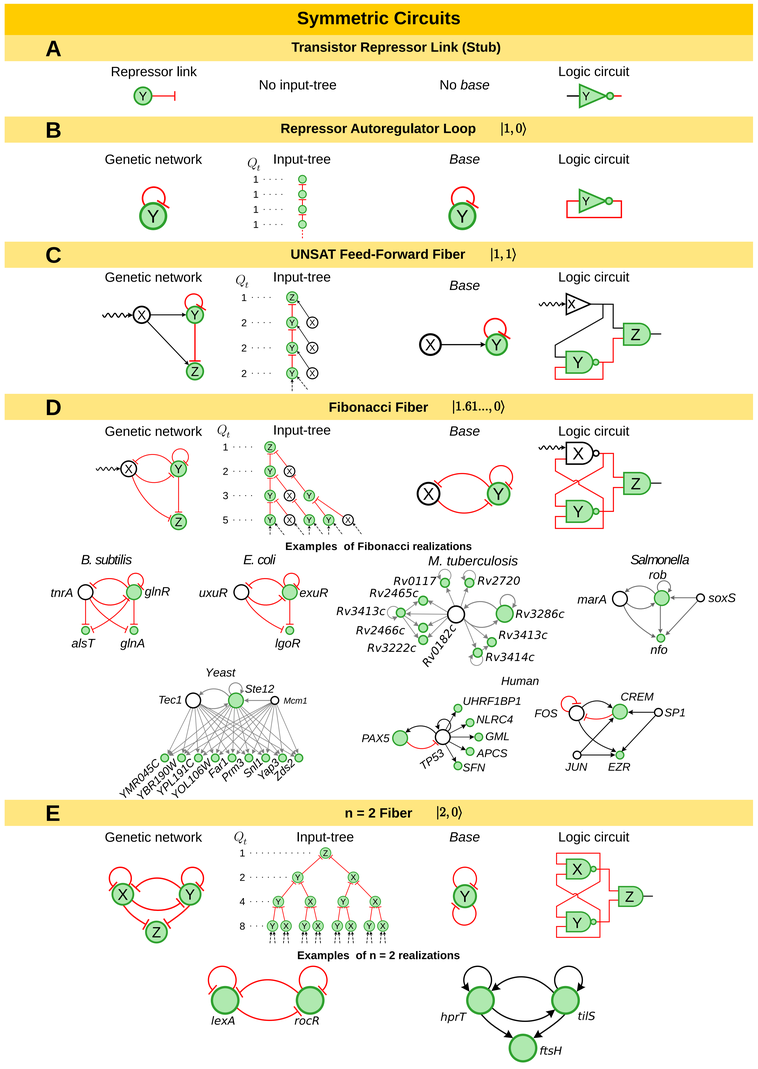
Fibration symmetries uncover the building blocks that perform core logic computations in biological networks

Leifer Ian, Morone Flaviano, Makse Hernan, The City College of New York

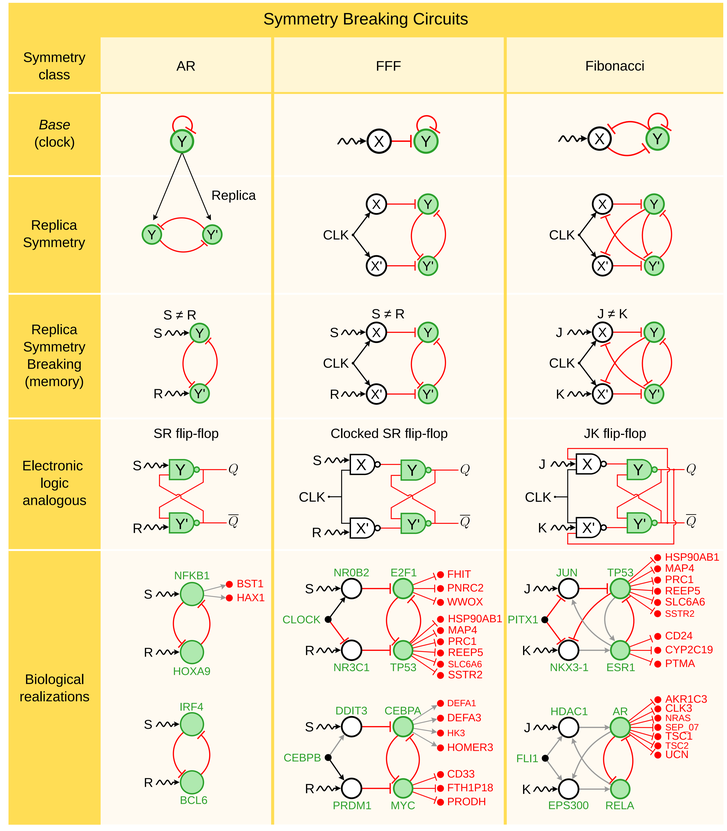
We introduce a graph representation of the information flow in the network as a set of input trees, one for each node, which contains all pathways along which information can be transmitted. In this representation, we find remarkable symmetries in the input trees that deconstruct the network into functional building blocks called fibers. Nodes in a fiber have isomorphic input trees and thus process equivalent dynamics and synchronize their activity. The building blocks are classified into topological classes of input trees. Logic computational circuits in gene regulatory networks arise from a fibration symmetry breaking in the network structure. We implemented a constructive procedure that reveals a hierarchy of genetic circuits, ubiquitous across species, that are surprising analogues to the emblematic circuits of solid-state electronics: starting from the transistor and progressing to ring oscillators, current-mirror circuits to toggle switches and flip-flops.



Definition of input tree, symmetry fibration, fiber, and base.



Hierarchy of symmetric circuits of increasing complexity. A is the simplest possible one. Repressor link turns A into B - circuit with repressor autoregulation with an input tree that feeds its own expression levels. Complexity is increased further in C, D, E. Logic circuits corresponding to symmetric circuits function as clocks.



Breaking the fibration symmetry of each circuit creates structures analogous to ‘flip-flops’ in electronics that store a bit of binary information into computer memory.

Conclusions:

- We introduced a theoretically principled strategy to search for computational building blocks in biological networks
- We implemented and ran the algorithm on multiple biological networks to obtain examples above and show their significance
- Presented strategy offers a systematic route to design synthetic biological circuits

1. Morone F, Leifer I, Makse HA. Fibration symmetries uncover the building blocks of biological networks. Proc Natl Acad Sci USA. 2020;117(15):8306-8314
2. Leifer I, Morone F, Reis SDS, Andrade JS, Sigman M, Makse HA. Circuits with broken fibration symmetries perform core logic computations in biological networks. PLoS Comput Biol 16(6): e1007776. (2020)