Synthetic Biology for Multiscale Designed Biomimetic Assemblies
From Designed Self-Assembling Biopolymers to Bacterial Bioprinting

Majerle, Andreja; Schmieden, Dominik T.; Jerala, Roman; Meyer, Anne S.

DOI
10.1021/acs.biochem.8b00922

Publication date
2019

Document Version
Accepted author manuscript

Published in
Biochemistry

Synthetic biology for multiscale designed biomimetic assemblies: from designed self-assembling biopolymers to bacterial bioprinting

Andreja Majerle,[1] Dominik T. Schmieden,[2] Roman Jerala,[1] Anne S. Meyer[3,*]

[1]Department of Synthetic Biology and Immunology, National Institute of Chemistry, Hajdrihova 19, 1000 Ljubljana, Slovenia

[2]Department of Bionanoscience, Kavli Institute of Nanoscience, Delft University of Technology, 2629 HZ Delft, The Netherlands

[3]Department of Biology, University of Rochester, Rochester, NY 14627, USA

[*]Correspondence: anne@annemeyerlab.org

Abstract

Nature is based on complex self-assembling systems that span from the nano- to the macroscale. We can already start to design biomimetic systems with properties that have not evolved in nature, based on designed molecular interactions and regulation of biological systems. Synthetic biology is based on the principle of modularity: repurposing diverse building modules to design new types of molecular and cellular assemblies. While we are currently able to use techniques from synthetic biology to design self-assembling molecules and re-engineer functional cells, we still need to use guided assembly to construct biological assemblies at the macroscale. We review the recent strategies to design biological systems ranging from molecular assemblies based on self-assembly of (poly)peptides to the guided assembly of patterned bacteria, spanning seven orders of magnitude.

Introduction

Biological systems are exceptionally complex, highly hierarchical in structure, and span a broad scale over ten orders of magnitude. Biological components range in size from nanometers to tens of meters, from single molecules to the largest organisms, respectively. Biological structures such as lipid membranes, higher-order structured proteins, or nucleic acids are formed exclusively through self-assembly, a bottom-up process where atoms or molecules associate in well-defined and functional assemblies under physiological conditions.[1] Naturally occurring self-assembly represents an attractive comprehensive tool and is a technologically feasible and cost-effective strategy for the design of new biomimetic systems or materials, functional biomaterials, or devices. In fact, the design of novel protein nanostructures can be achieved based on the fundamental biophysical principles of protein self-assembly, whereas the idea of modular design based on preformed building blocks has been central to the design of higher-ordered nanostructures and biomaterials.[2]

In recent decades, multiple methods and technologies have been applied to elucidate the principles of natural self-assembly processes and to design new approaches aimed at assembling biomolecules, cells, and tissues.[3,4,5,6] On the

molecular scale, we can already design or guide interactions between individual molecules, although self-assembly approaches typically produce results that are far superior. Self-assembly extends up to the macroscopic scale in natural biological systems, although we currently lack full understanding of the principles that define the structure and function of individual cells. The deficits in our knowledge are even greater for cellular differentiation and formation of multicellular tissues, organs, and whole organisms. Formation of multicellular systems is typically slow and may take days to years for the complete development of the organism. The structure of multicellular organisms is to a large degree hardwired within the genetic program, although external forces and epigenetic elements can have important effects on the shape and properties of the mature organism. The principles of self-assembly of complex multicellular organisms remain to a large degree unknown and will probably take several decades to fully understand and be applied to fundamentally redesigning the self-assembly of multicellular organisms.

While self-assembly is highly desirable for engineered biological systems, guided assembly aimed at imposing a desired arrangement of molecules and cells can be used as well to direct the formation of biological systems. While nanostructures are too small to be produced efficiently by any other method apart from self-assembly, guided assembly based on coupling of selected physiochemical signals or the use of external fields or conditions can be applied to generate patterns that guide the ordering of cells. Although a rich diversity of complex multicellular organisms exists in nature, self-assembly can likely only be used to guide a limited number of structures. Additionally, the process of formation of a multicellular organism is very complex and difficult to engineer. Patterning by external inputs, such as light, or acoustic or magnetic fields, can help compensate for our current inability to guide the self-assembly of multicellular organisms, enabling the formation of shapes that may be difficult if not impossible to reach by self-assembly and speeding up the process of macroscale shape formation. Therefore, multiscale synthetic biology approaches are being developed to direct the assembly of building blocks into hierarchically ordered structures using a combination of self-assembly and guided assembly strategies. This approach offers the potential to build designed, nanostructured biomaterials with higher complexity of structure and/or function on multiple length scales.

In order to create biomimetic systems, synthetic materials must be developed that can recapitulate the structural and functional complexity of biological materials. Such biomimetic assemblies could be formed by self-assembly of polypeptides or cells, without or in combination with different organic and inorganic compounds, nanoparticles, or scaffolds, or via assembly guided by external inputs or conditions. The design of biomimetic materials is ready to face more complex challenges such as the introduction of functions or the development of medical and nonmedical applications. Here we review recent examples and discuss self-assembly and guided assembly strategies in synthetic biology and their advantages and disadvantages for the design of novel biomimetic assemblies across different scales, from *de novo* designed biopolymers to guided assembly of patterned bacteria, and discuss future perspectives and potential applications.

Designed self-assembly of biopolymers

Self-assembling biomacromolecules, including nucleic acids, peptides, proteins, lipids, and carbohydrates, are the fundamental building blocks of life. Large macromolecular assemblies, composed of tens to thousands of polypeptide chains, are widespread in all cell types and come in many shapes and forms. Single-chain biomolecules range in size from hundreds- to mega-Daltons, with the largest polypeptide chain, titin, composed of ~ 30,000 residues that form 244 folded protein domains, exceeding 1 μm in length.[7] This example demonstrates that biological systems can produce quite large building molecules if their assembly is modular and folding is not a limiting factor.

One major approach for designing biologically active high-order structures or materials is the **self-assembly of polypeptides**. Polypeptide sequences often include different types of domains within the same chain and can rapidly self-assemble under normal physiological conditions into complex and well-defined structures with a precise spatial arrangement of functional groups[8]. Given their enormous variability in sequence and structure, proteins appear to have nearly unlimited functional potential under conditions conducive to life. While DNA nanotechnology has demonstrated the repurposing of natural building materials for the construction of simply and completely designed shapes, polypeptide nanotechnology has clear advantages due to the versatility of chemistries and geometries allowed in polypeptide building. Additionally, polypeptides can be efficiently, sustainably, and cost-effectively produced by cell factories via environmentally-friendly methods.[9]

Proteins self-assemble based on the formation of a large number of long-range weak cooperative interactions between atoms of a linear polypeptide chain, which may be difficult to accurately predict. Therefore, modularity of the design can enable the construction of large designed proteins. Novel peptide and protein nanostructures can be developed by combining and re-engineering already-existing protein domains through protein fusion or protein interface design, or by designing peptides and proteins *de novo*. Despite the complex interplay of interactions that determine the 3D structure of proteins, researchers recently succeeded in making a breakthrough by designing bio-inspired assembled protein structures that do not exist in nature.[10,4]

***De novo* design of multiple-chain peptide assemblies** has yielded an array of increasingly complex nanostructures[11]. α-helix bundles were one of first *de novo* designed multiple-chain assemblies[12,13], which were later used for the design of multiple multi-chain nanostructures, including cages[14] and nanotubes.[15] ***De novo* design of multi-chain protein assemblies** was developed to design protein assemblies employing natural oligomerizing domains, e.g. monomers, which assemble with a specific symmetry.[16,17,18] Yeates et al. used natural dimerizing and trimerizing domains fused into a single polypeptide chain, which self-assembled into protein cages with tetrahedral, octahedral, or icosahedral symmetry, layers, crystals and filaments.[16]

More recently, Baker et al. demonstrated self-assembly of oligomerizing domains, where cage-like proteins were designed with tetrahedral or octahedral symmetry (**Fig. 1A**)[17] as well as a 600-kDa protein homododecamer that self-assembled into a symmetric tetrahedral cage.[18] Fallas and Hartgerink have described a multistate computational design protocol for the design of three peptides that fold into a highly stable ABC heterotrimer.[19] A related approach to design self-assembling nanostructures is based on the **engineering of protein-protein interfaces.** In this technique, computational methods are used to design the structural complementarity to direct the assembly, providing the driving force for the assembly and for the definition of the relative orientations of the building blocks. Based on this strategy, different 24-subunit cage-like protein nanostructures were designed that combined trimeric subunits that co-assembled into a symmetric tetrahedral architecture[20]. Two-component building blocks (pentamers and trimers) were combined to form 120-subunit icosahedral protein nanostructures (**Fig. 1B**),[21] and self-assembled unilamellar spheres were constructed from building modules comprised of two noncovalent heterodimeric and homotrimeric coiled-coil bundles.[14] These achievements were made possible by the advances in computational molecular modeling tools, notably the Rosetta software pioneered by the Baker group.[22]

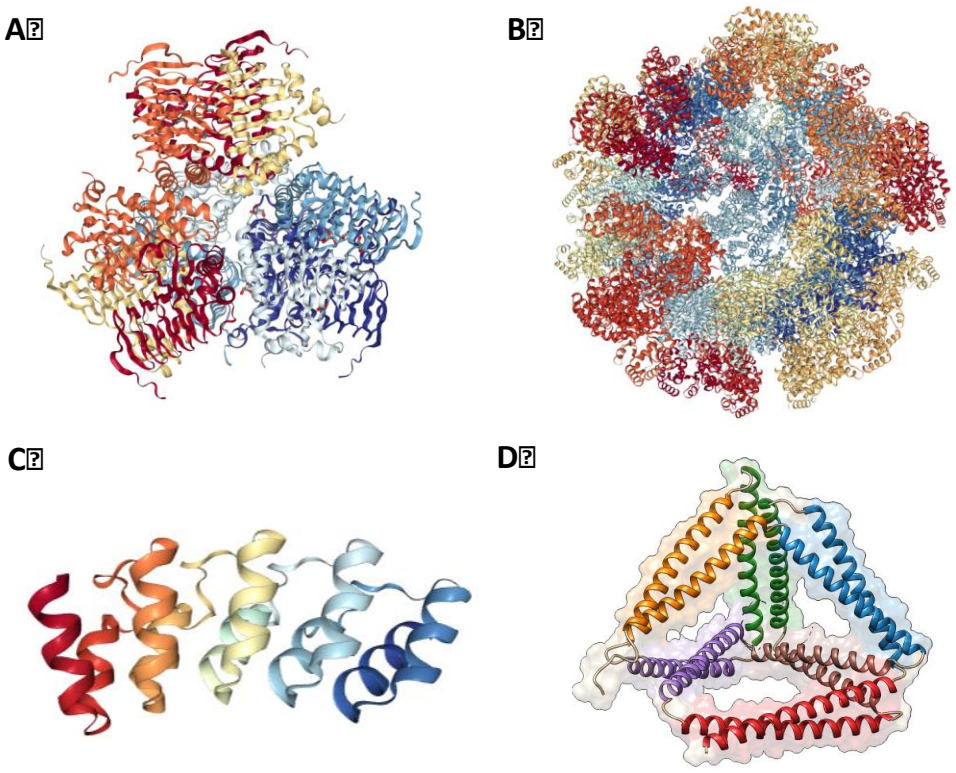

Figure 1. Different types of designed self-assembling proteins. **A.** Fused oligomerizing domain tetrahedral cage.[17] **B.** Icosahedral assembly based on a designed protein interface.[21] **C.** Repetitive protein.[23] **D.** Coiled-coil protein origami tetrahedral cage.[33]

Modular designed single-chain protein assemblies were initially assembled from repeat proteins, where the regularity of their inner structure as assessed by repetitive short- and medium-range interactions defines the

curvature and pitch of the assemblies (**Fig. 1C**).[23,24,25] The first examples of non-repetitive single-chain protein nanostructures made by this design strategy were α-helical bundles that relied on short-range interactions.[26] As an upgrade to introduce long-range intramolecular interactions in order to design complex modular structures, Jerala and colleagues translated the concept of DNA nanotechnology[27] into polypeptides.[28] In this approach, α-helical coiled-coil dimers, one of the best-understood protein structure motifs,[29,30] provided orthogonal pairwise-interacting modules reminiscent of the complementarity of nucleic acids. Designed Coiled-coil Protein Origami (CCPO) structures were based on coiled-coil segments as distinct structural elements that were arranged in a defined order to define the path of the polypeptide chain to form edges of a stable polyhedral protein cage. Dimers composed of coiled-coil peptides were formed by a polypeptide double Eulerian path, which promoted folding into a desired protein fold.[31] This strategy was first applied to design a single-chain polypeptide tetrahedral fold[32] and further utilized to design different single-chain coiled-coil protein origami structures of increasing complexity and size, i.e. polyhedron-shaped protein cages (**Fig. 1D**). The largest cage (a triangular prism) consisted of 700 amino acid residues and represents one of the largest single-chain protein designs.[33] Additionally, supercharged orthogonal coiled-coil elements with negatively charged residues at non-interacting positions[34] were employed to chaperone the correct *in vivo* self-assembly under physiological conditions.

Guided assembly of biopolymers

While self-assembly dominates the formation of complex biomolecules, molecular assembly can be also guided by the chemical activity of small or large molecules or by different physical signals. One frequently used strategy for guided molecular assembly is **coordination through metal ions**. α-helical bundles, nanotubes, and two-dimensional arrays have been assembled through natural metal binding sites.[35] Additionally, *de novo* metal binding protein interfaces can be engineered into proteins.[36] Metal-site design can be used also for controlling the assembly of coiled-coil peptides.[37] Environmental oxidation conditions have been used to guide **redox-sensitive** protein assemblies (e.g. self-assembly interfaces sensitive to the redox state in the cell, through disulfide bond formation).[38] **Phosphorylation** state can also influence the self-assembly of proteins,[39] which has allowed the design of reversible molecular switches.[40] In **protease-responsive modules**,[41] an inhibitory domain is cleaved off to endow responses to selective proteases that are active under certain cellular conditions or upon interaction with pathogens. This approach has been implemented in an example of designed cross-linked supramolecular filaments that dissociate into less stable micellar assemblies and monomers upon proteolytic activity of matrix metalloproteases-2[41] or by designed coiled-coil mediated assemblies.[42] In **chemically-induced dimerization,** a protein complex can assemble by the addition of a chemical signal triggering an interaction between the receptor domains (e.g. rapamycin-triggered FKBP-FBP or abscisic acid-triggered heterodimerization of Pyl-ABI), which can mediate the assembly of other protein domains.[43] **Temperature**-responsive behavior of designed proteins is based on the (de)stabilization of protein domains or assemblies.[44] The amino acid residues histidine, aspartic acid, and glutamic acid are frequently responsive to conformational changes in a range of **pH** values between 3

and 7.[45,46] Protein assembly can also depend on **ionic strength**,[47] **solvent polarity**,[48] or **mechanical stimulation**.[49] **Light**-triggered response of protein-based materials can be established by photochemical crosslinking reactions with polymeric materials,[50] based on the introduction of light-responsive LOV domains[51] or other light-inducible oligomerization domains.[52] The assembly of protein nanostructures can also be guided via non-covalently[53] or covalently[54] linked **polymer-protein conjugates** or the formation of hybrid **protein-nanoparticle** complexes.[55] Guided assembly can be combined with **patterning** or **immobilization of protein molecules onto functionalized surfaces** and used for the generation of complex bioactive scaffolds for applications such as drug discovery.[56]

Designed patterning of bacteria

While designed intermolecular interactions can be used to guide the self-assembly of protein complexes, the large-range order required to create multi-cellular assemblies makes this approach still too challenging. Therefore, patterns may be imposed onto populations of cells by external signals in combination with synthetic biology approaches to engineer specific cellular responses. Initially-homogeneous groups of bacteria can be induced to express genes differentially under the control of **chemical inducers**, either externally applied or self-produced. This approach opens the possibility to employ a large range of natural abilities in new ways, resulting in emergent patterning that is comparable to the development of animal tissues. In one early example, *Escherichia coli* bacteria were designed to produce fluorescent proteins in response to a quorum-sensing signaling molecule diffusing away from a point source. Expression of the fluorophore within a lawn of bacteria was de-repressed only at intermediate concentrations of the chemical inducer, such that a bulls-eye pattern of fluorescence could be established.[57] Similar band-pass filters have also been implemented into lawns of *Lactobacillus lactis* in combination with applied masks of diffusing inducer chemicals, creating fluorescent line patterns of arbitrary 2D geometries and tunable thickness (**Fig. 2A**).[58] A cell-density-sensing system was later employed to control the expression of a chemotaxis regulatory protein, such that the *E. coli* bacteria themselves became arrayed in rings of alternating high and low density of tunable wavelength.[59] A higher degree of self-regulation of bacterial patterning was achieved when more complex genetic circuits acting as an AND gate were constructed in *E. coli* to create three-color patterns in response to self-produced inducers.[60] Recently, *E. coli* were engineered to express a synthetic genetic circuit that spontaneously creates stable disordered Turing patterns, exhibiting high spatial resolution and independence of pattern formation with low control over the final shape and position of the pattern.[61]

While chemical inducers have proven to be useful tools in pattern formation, they are subject to the laws of diffusion, resulting in slow spread over longer distances, loss of directionality, and poor control over the induction strength in different regions of the culture. A promising alternative to chemical inducers is the control of bacterial pattern formation with light, which can allow for high-resolution patterning with stringent control. In early proofs-of-principle of **light-induced patterning** in bacteria, light-sensing systems from cyanobacteria were transferred to engineered *E. coli* to create strains that acted as edge detectors[62] or that could upregulate the transcription of

desired genes orthogonally in response to two different wavelengths of light.[63] Recently, light induction has been applied to regulate bacterial attachment via several different techniques. Proteins that interact via reversible photo-switching were exploited by expressing one of the proteins on the surface of *E. coli* bacteria and conjugating its partner to a glass substrate, after which the application of a photomask allowed for the bacteria to adhere to the substrate in controlled, reversible patterns.[64] Photo-inducible expression of an adhesion gene in *E. coli* upon stimulation with patterned light was next used to create spatially patterned biofilms via a more streamlined but non-reversible approach.[65] Light-induced biofilm attachment has also been achieved in engineered *Pseudomonas aeruginosa* by introducing light-sensing systems to control the expression and/or degradation of biofilm signaling molecules (**Fig. 2B**).[66,67]

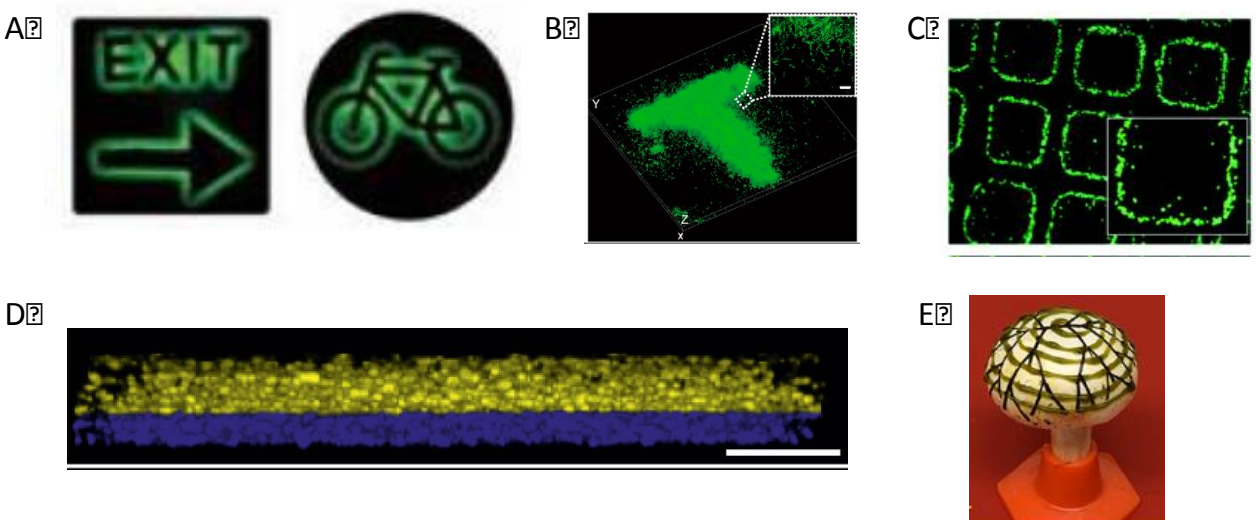

Figure 2. Bacterial patterning. **A.** Genetically engineered band-pass filters that respond to chemical inducers.[58] **B.** The letter "T" bioprinted in *P. aeruginosa* biofilms via optogenetics.[67] **C.** Patterning of individual *Staphylococcus aureus* bacteria through selective surface modification.[69] **D.** Layered bacteria achieved with 3D printing.[78] **E.** A 3D-printed bionic mushroom incorporating cyanobacteria and graphene for generation of photocurrent.[80]

Genetic engineering and control with chemicals or light to induce bacterial patterning will likely continue to be used extensively due to their proven efficacy in combination with the ever-increasing number of sequenced and examined genetic systems from which parts and chassis may be chosen. However, the patterned bacteria need to be genetically engineered, noisy logic gates might be needed, the number of variants of e.g. quorum sensing proteins and sensors is limited, and control is realized by diffusing inducers. Together, these factors make fine-tuning and up-scaling of these patterning systems slow and laborious. In addition, the absolute dimensions of the produced bacterial patterns are typically small, usually in the millimeter- to centimeter-scale range in the x/y-plane, but only in the tens of micrometer range in the z-direction. Consequently, these methods are not currently suitable for patterning of bacteria in larger volumes—an important pre-requisite for producing materials for practical applications.

Guided assembly of patterned bacteria

Current methods for the designed patterning of bacteria excel at patterning cells with a high resolution, but they require genetic engineering of the bacteria and have thus far not been used to pattern more than one species at a time. To achieve the patterning of unmodified bacteria, several guided-assembly techniques have been developed. To generate **selective surface modification**, substrates were etched with an ion beam to expose only specific areas for the attachment of a cross-linker. This cross-linker, in turn, bound antibodies specific to the fimbriae of *Salmonella enterica* serovar Typhimurium, allowing for the specific and patterned binding of *Salmonella* bacteria to the modified surface while other bacteria species in a mixed culture did not adhere.[68] If high selectivity is not required, then simpler surface modifications can be employed. For example, polystyrene surfaces were modified by applying a copper-grid mask while UV cross-linking an amphiphilic block co-polymer onto the surfaces, resulting in defined areas of increased surface hydrophilicity. These surface structures allowed cultures of *Staphylococcus aureus* to bind selectively to these areas even down to a resolution of a single bacteria-width, despite the tendency of *S. aureus* to form clusters (**Fig. 2C**).[69] A straightforward variation of this approach was used to pattern multiple species of bacteria on agar plates by exploiting their differential susceptibilities to antibiotics. Agar was supplemented with a photo-activated antibiotic that was selectively activated with a mask and a UV lamp, resulting in different antibiotic concentrations depending on the length of UV exposure. A mixture of *E. coli* and *M. luteus* plated onto these plates resulted in areas where *M. luteus* grew exclusively, due to its high resistance to the antibiotic, and mixed areas where both bacteria survived.[70]

Wild-type bacteria can also be patterned via **encapsulation with photochemistry**.[71] Using a laser-based lithography technique, bacteria were suspended within a solution containing gelatin and a photosensitizer. Multi-photon lithography was then applied to induce cross-linking at the focus points of the laser, allowing for the fabrication of arbitrarily-shaped, 3D micro-environments with micrometer resolution. The structural components were permissive for small molecules such as nutrients and antibiotics while reliably containing bacteria within the compartments, allowing for investigation of bacterial interspecies interactions by surrounding a colony of one species by a colony of a second species.[71] Surface modification for selective bacteria attachment and encapsulation via photochemistry both allow for very high resolutions without requiring genetic engineering of bacteria. Photochemistry-based encapsulation allows for a wide variety of geometries to be produced, and the selectivity of surface modification can be flexibly tuned depending on the application, from simple increase of surface hydrophilicity to the use of highly selective antibodies, of which many are commercially available. Both approaches require highly specialized technologies, in the form of multi-photon laser writing or microfabrication techniques for substrate modifications or the production of masks, depending on the complexity and dimensions of the pattern applied.

The high precision of machines used in printing and microfabrication makes the small size of bacteria less of a confounding factor in patterning, allowing for approaches where bacteria can be placed directly by a pumping

system or tiny, microfabricated structures. **Microfabrication** has been used to create PDMS stamps with pillars as small as 1 μm in diameter to transfer cells from a lawn of *E. coli* onto an agarose substrate, producing arrays of groups of bacteria. By reducing the number of bacteria in the initial bacteria lawn, arrays of bacteria could be produced with single-cell resolution.[72] Fabricated PDMS stencils have also been applied to produce arrays of biofilms of several Gram-positive and -negative bacteria species on different substrates. This technique is suitable for batch cultures as well as culture in microfluidic devices and has produced biofilms with dimensions in the tens of micrometers, with further down-scaling expected to be possible.[73] Microfabricated tools allow for very high resolutions, but scale-up and the use of different cell types can be a challenge. Furthermore, specialized microfabrication facilities and trained staff are required to produce the stamps and stencils.

To deposit bacteria via a more accessible approach, commercial **inkjet printers** have been employed to deposit suspensions of *E. coli* onto agar-coated glass slides, reaching resolutions of 100 colonies/cm^2 and achieving single cells per droplet by adjusting the concentration of cells in the printed suspension. Despite the high temperatures used in the printheads to generate droplets, the printed bacteria were viable.[74] A similar approach was later used to print bacterial dots with a diameter of 100 μm and a density of 400 dots/cm^2 onto agar-coated glass slides. By printing gradients of antibiotic solutions, inkjet printing was used as a high-throughput replacement for the traditional disc diffusion method of determining minimum inhibitory concentrations.[75] Inkjet printing is a compelling technique, due to the low cost of commercial printers, their high precision, the ability of control with standard software, and the ease of modification for biological purposes. Challenges arise from cross-contamination when more than one species/strain is printed, the difficulty of sterilization of e.g. the print head, and clogging through dried growth medium components or carrier substances.

For applications requiring macroscopic 3D structures and flexibility in the choice of bacterial species, additive manufacturing has recently emerged as a promising tool. The Meyer lab re-fitted a commercial **3D printing** kit into a 3D printer for bacterial cells that extrudes bioink, a mixture of bacteria, nutrients, and an alginate solution that solidifies into a gel upon contact with a calcium-ion rich substrate. The printed *E. coli* cells could be arranged in stable, layered structures, while still being accessible to nutrients and chemical inducers for the controlled activation of engineered genes.[76] Thereafter, applications of 3D-printed bacteria were demonstrated for bioremediation when *Pseudomonas putida* was printed and fixed in a UV-cross-linkable bioink, resulting in a mesh-shaped living material that successfully degraded phenol present in the surrounding medium. The potential for materials production for biomedical applications was also demonstrated when *Acetobacter xylinum* was printed in a complex 3D shape to cover the face of a doll, which had been scanned to provide the printing co-ordinates. The bacteria subsequently produced cellulose in situ that remained in the printed shape after removal of the biological residues, showing a path towards using 3D-printed bacteria for the production of personalized skin grafts.[77]

Recently, K'NEX toys were used to create the lowest-cost 3D bioprinter to date. This 3D printer was used to extrude *E. coli* engineered to express curli fibers, the major proteinaceous component of *E. coli* biofilms, in the presence of a

chemical inducer. After a post-printing induction period, the printed structures became resistant to the strong alginate-dissolving agent citrate, showing that exogenous control over biofilm formation can be up-scaled to the macroscale to generate stable, living materials (**Fig. 2D**).[78] 3D printing techniques have also been applied to encapsulate engineered *Bacillus subtilis* biofilms inside of hydrogels through sequential printing of hydrogel and biofilm-producing layers. When 3D-printed *B. subtilis* biofilms were transferred onto a fresh agar plate, the printed samples were able to self-regenerate biofilm growth on the plate in the same geometrical pattern as the initial print, showing the potential of this approach to create long-term, transferrable bacterial patterning.[79] 3D printing has also been applied to create "bionic mushrooms" by 3D-printing layers of cyanobacteria and graphene nanoribbons onto mushroom caps (**Fig. 2E**). The mushrooms were able to nourish and sustain the cyanobacteria over an extended period of time, during which the bacteria produced electricity that was harvested via the conductive graphene ribbons. This creative work shows the potential benefits that can arise from creating an artificial, spatially-patterned symbiosis between different kingdoms of life.[80]

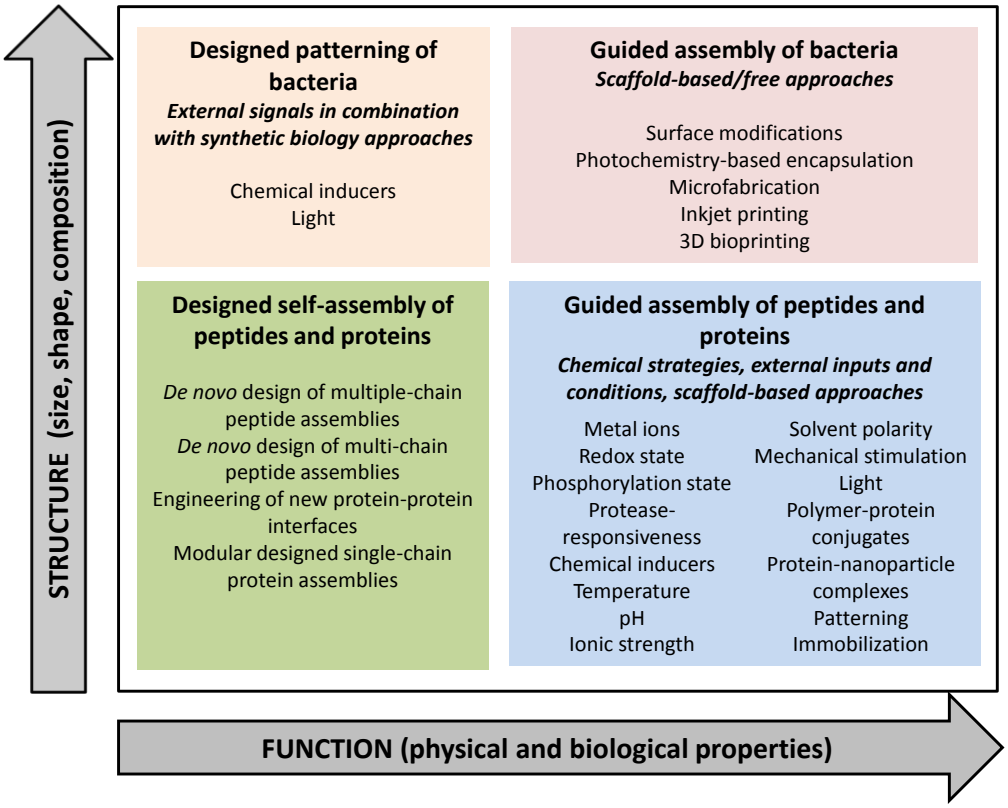

Figure 3. The strategies and methods for assembly of bionanostructures and biomaterials. The hierarchy of complexity of assembled biological structures increases from designed (poly)peptide nanostructures at the molecular and nanoscale to designed bacterial biomaterials at the micro- and macroscale. The complexity of physical and biological functions of designed assemblies of (poly)peptides and bacteria increases from self-assembling to guided assembly approaches.

Challenges and perspectives

One of the most active areas of innovation for the development of novel polymeric nanomaterials is in self-assembly processes that can be tuned via external inputs into the system. In this article we review developments and strategies at two extremes of synthetic biology approaches, ranging from the design of new nanoscale molecular assemblies such as self-assembling polypeptides, to guided macroscale patterning of bacterial cells, to illustrate recent progress and current challenges (**Fig. 3**). While we are already able to engineer self-organizing patterns of bacteria, macroscale patterning can still primarily be addressed by guided assembly approaches.

Building synthetic biological structures by assembling biomolecules in an organized way is a rapidly growing field of research involving intense interdisciplinary collaboration. Structure-based computational protein design strategies have been demonstrated to be a powerful tool for engineering new functional capabilities that extend beyond biomimicry. As we have illustrated, diverse approaches to the design of novel protein nanostructures with tunable dimensions, morphology, and functionality have recently emerged and are continuously being improved, where structural elements as small as short peptides can already form nanoscale-ordered assemblies.[10,4]

Among those approaches, one of the main strategies continues to be the *de novo* design of polypeptide assemblies, where reduction of the design complexity has been made possible by symmetry-aware algorithms, where (poly)peptide building blocks are docked together symmetrically, or modular design, which prioritizes the stability of the building elements. A wide range of self-assembling polypeptide nanomaterials has already been developed[81,82] and implemented in many biomedical applications for therapy, prevention, and diagnostics such as drug delivery and targeting,[83] epitope scaffolding for vaccination,[84] an alternative strategy for microvascular anastomosis using a peptide-based hydrogel,[85] alternative antimicrobial strategies using virus-inspired artificial capsids,[86] a strategy for the delivery of nucleic acids with artificial viruses,[87] and many others. Self-assembling polypeptide-based materials have also been used in applications in non-medical areas such as the rational design of protein molecular machines (e.g. biocatalytic nanomaterials,[88] sensors for electrochemical applications,[89] or optical-biosensor applications[90]) and functional materials (e.g. protein nanowires[91] or free-standing protein films[92]). Protein self-assembly includes certain limitations (e.g. most proteins are vulnerable to extreme chemical conditions such as pH, ionic strength, and temperature), so the construction of ordered protein assemblies needs an adaptable design and accurate control under strict conditions. On the other hand, environmental responsiveness also represents an advantage for the construction of dynamic assemblies with advanced functionalities, as one of the ultimate goals in this field. The capability of engineered biomaterials for **programmed responses to external stimulations** can lead to a panoply of different designed functions, such as specific targeting, controlled release, or improved efficacy. These “smart” behaviors can be combined for the construction of highly selective delivery systems, for complex conformational changes in highly-ordered structures, or for reversible phase transitions and mechanical properties[93,94] important for the design of dynamic features in advanced bionanostructures and biomaterials.

Synthetic biologists are increasingly turning their attention to the creation of **large engineered biological structures**, for example eukaryotic cells assembled into artificial 3D tissues structurally organized on multiple levels. For building such large biological structures, biological building blocks, which currently fall into the nano- or microscale range, must be extended into the macroscopic range. The design of self-assembling macroscale assemblies poses a formidable challenge in synthetic biology. Nature has solved these problems both for multicellular organisms as well as at the scale of individual cells, where oscillations and concentration gradients can be used to define organization at the macroscale.[95,96] Biomolecular self-assembly from a diverse array of multiscale building blocks, from polypeptides up to cells, is ultimately driven by noncovalent interactions.[1] It is currently easier to organize micro- or macro-biostructures such as artificial tissues by the use of external inputs, including magnetic fields,[97,98] acoustic waves,[99] geometric docking,[100] liquid-based templates,[101] or bioprinting[102] that can trigger and/or drive self-assembly of building blocks. Field-directed self-assembly (i.e. controlled by light, magnetic fields, etc.) has the added advantage that fields can be switched on/off and tuned dynamically, which enables improved long-range order and controlled orientation. Currently, other synthetic biology approaches are being developed for building larger structures composed of interacting cells, based e. g. on the deployment of synthetic cell-surface receptors that sense the types of neighboring cells and trigger their own differentiation, as was recently demonstrated by a combination of synthetic Notch receptors and cadherins.[103]

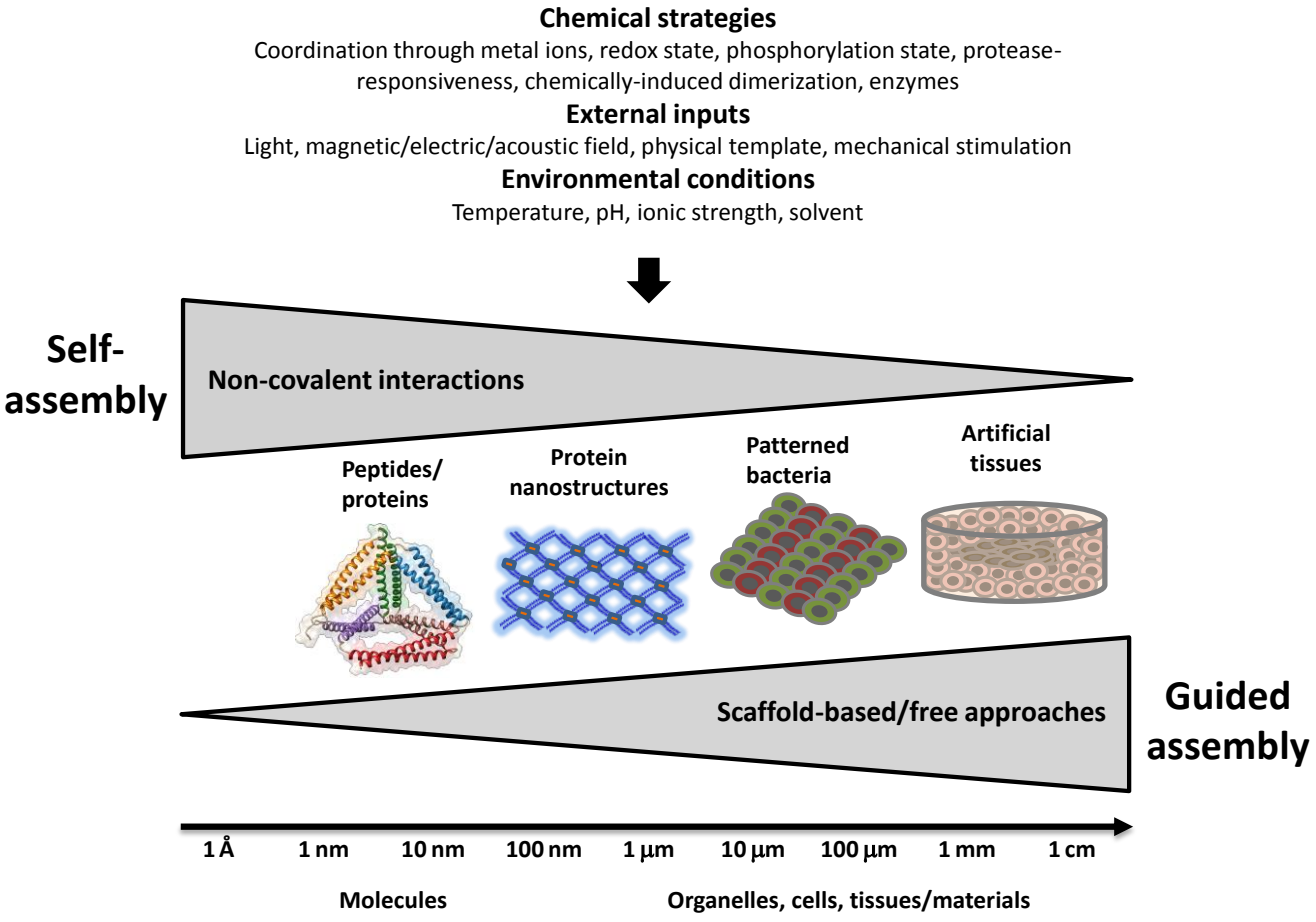

Figure 4. Self-assembly and guided assembly strategies for biomolecular construction can create designed biological systems spanning multiple length scales.

Nowadays, most tissue engineering approaches require the use of a patterned substrate (e.g. hydrogels) that mimics extracellular matrix to assist cells in the assembly process. In contrast, a different type of approach uses spheroid formation to provide a scaffold-free environment for 3D cell culturing.[104] Between those extremes there are multiple additional scales, such as the internal structuring of cells, where molecular assembly is being extended towards the microscale by diverse methods of pattern formation that can also exist under cell-free conditions [95,96]. The synergistic combination of both technologies, where self-assembly dominates ordering at the molecular level and guided assembly directs order at larger length scales with scaffold-based/scaffold-free approaches and the use of different chemical strategies, external inputs, or environmental conditions, promises to advance solutions for precision, repeatability, and high-throughput processing to develop complex assemblies at scales from nano- to macroscale, from protein nanostructures to the patterning of bacteria or the formation of artificial tissues (**Fig. 4**). In such an active and diverse field of research, where biotechnology meets nanotechnology and materials science, we have without question missed some interesting reports about novel protein nanostructures or biomaterials and their use in applications.

Long-term vision for multi-scale assembly

Protein design and engineering in synthetic biology are moving **towards the functional design** of smart biological parts, devices, and systems that will be based on self-assembly and will be responsive to diverse signals. The future is likely to bring the development of structures and systems that will actively interface with a complex biological environment, for example, advanced bionanostuctures or biomaterials for therapeutic delivery that will shield the sensitive molecular cargo, target specific cells or tissues, and release cargo at the appropriate site of action.
An additional level of complexity will be the ability to coordinate multicellular events in order to assist in the organization of multiscale tissues, for example in tissue integration and regeneration. One promising example in this area is nanocages: protein assemblies that show a great potential to be developed into artificial stimuli-responsive or programmable bionanomachines functioning as drug/gene carriers, biosensors, imaging agents, vaccine/immuno modulators, or nanoreactors for biocatalysis.[105] Currently, clinical applications of self-assembled protein nanocages are still limited,[106] but further engineering and introduction of responsiveness to molecular or environmental signals will bring solutions for the enhancement of their targeting capacity or penetration efficiency. We can also expect new abilities for nanocages to modulate the immune response and to feature enhanced biocompatibility and biodegradability via engineering of external cage surfaces.

For multi-scale assembly, we can envision exciting potential in the introduction of dynamic features (e.g. incorporating degradation or signal-responsiveness into biomaterials) or the introduction of non-biological moieties to biological systems, such as bio-inert micro- and nanocarriers. We also anticipate the realization of engineering paradigms that have been so far used only in non-biological engineered systems, including standardization,

reliability, and predictability. We expect numerous benefits based on the productive merging of features of the two worlds for the benefit of human health, industrial production, and the environment.

It seems at first glance that bioprinting might eventually not be required at all if self assembly could be programmed into designed biological systems similarly to the differentiation programs of plants and animals. Bioprinting could nevertheless provide a much faster means to assemble macroscopic tissues and to fabricate shapes and functional assemblies that could be very difficult if not impossible to encode into the genetic program. To promote the accessibility of this promising new technology, attention should be paid to developing a new generation of 3D bioprinters that are dramatically lower in cost but can still accommodate multi-channel printing and bio-inks of a variety of viscosities with minimal sample heating.

For future construction of advanced complex biological and biomimetic structures, up to artificial tissues, we will need to combine both a deeper understanding of naturally evolved systems, from proteins to tissue architecture and differentiation, and advances in analytical and manufacturing technology and multi-scale modeling. The fast-growing field of computation-aided structural protein design has already significantly enhanced efforts in protein-based nanomaterial design by automating structure and function prediction. In the future, massively parallel approaches for *de novo* protein design will transform computational protein design into a data-driven big science that will utilize deep learning algorithms and methods.[107] In addition to the Internet of Things (IoT), we may also move towards the Internet of Biological Things (IoBT), where synthetic biology and nanotechnology tools will allow the engineering of biological embedded computing devices for a vast array of applications pertaining to health, energy, and the environment.

Acknowledgments

This project was financed by the Slovenian Research Agency (PP4-0176, N4-0037, N4-0080) and by the M-ERA project MediSURF (Reference Number: project 3193). Contribution of the COST actions CM-1306 and CM-1304 is acknowledged. This work was also supported by the Netherlands Organization for Scientific Research (NWO/OCW), as part of the Frontiers of Nanoscience program, as well as the University of Rochester Department of Biology.

References

(1) Whitesides, G. M., and Grzybowski, B. (2002) Self-assembly at all scales. *Science 295*, 2418–21.

(2) Norn, C. H., and André, I. (2016) Computational design of protein self-assembly. *Curr. Opin. Struct. Biol. 39*, 39–45.

(3) Avinash, M. B., and Govindaraju, T. (2014) Nanoarchitectonics of biomolecular assemblies for functional applications. *Nanoscale 6*, 13348–13369.

(4) Luo, Q., Hou, C., Bai, Y., Wang, R., and Liu, J. (2016) Protein Assembly: Versatile Approaches to Construct Highly Ordered Nanostructures. *Chem. Rev. 116*, 13571–13632.
(5) Athanasiou, K. A., Eswaramoorthy, R., Hadidi, P., and Hu, J. C. (2013) Self-Organization and the Self-Assembling Process in Tissue Engineering. *Annu. Rev. Biomed. Eng. 15*, 115–136.
(6) Bishop, E. S., Mostafa, S., Pakvasa, M., Luu, H. H., Lee, M. J., Wolf, J. M., Ameer, G. A., He, T. C., and Reid, R. R. (2017) 3-D bioprinting technologies in tissue engineering and regenerative medicine: Current and future trends. *Genes Dis. 4*, 185–195.
(7) Krüger, M., and Linke, W. A. (2011) The giant protein titin: A regulatory node that integrates myocyte signaling pathways. *J. Biol. Chem. 286*, 9905–9912.
(8) Lupas, A. N., and Alva, V. (2017) Ribosomal proteins as documents of the transition from unstructured (poly)peptides to folded proteins. *J. Struct. Biol. 198*, 74–81.
(9) Demain, A. L., and Vaishnav, P. (2012) Production of recombinant proteins by microbes and higher organisms. *Biotechnol. Adv. 27*, 6–7.
(10) Huang, P.-S., Boyken, S. E., and Baker, D. (2016) The coming of age of de novo protein design. *Nature 537*, 320–327.
(11) Raymond, D. M., and Nilsson, B. L. (2018) Multicomponent peptide assemblies. *Chem. Soc. Rev. 47*, 3659–3720.
(12) Regan, L., and DeGrado, W. F. (1988) Characterization of a helical protein designed from first principles. *Science 241*, 976–978.
(13) Hecht, M. H., Richardson, J. H., Richardson, D. C., and Ogden, R. C. (1990) De Novo Design, Expression and Characterization of Felix: A Four-Helix Bundle Protein of Native-Like Sequence. *Science 249*, 884–891.
(14) Fletcher, J. M., Harniman, R. L., Barnes, F. R. H., Boyle, A. L., Collins, A., Mantell, J., Sharp, T. H., Antognozzi, M., Booth, P. J., Linden, N., Miles, M. J., Sessions, R. B., Verkade, P., and Woolfson, D. N. (2013) Self-Assembling Cages from Coiled-Coil Peptide Modules. *Science 340*, 595–599.
(15) Burgess, N. C., Sharp, T. H., Thomas, F., Wood, C. W., Thomson, A. R., Zaccai, N. R., Brady, R. L., Serpell, L. C., and Woolfson, D. N. (2015) Modular Design of Self-Assembling Peptide-Based Nanotubes. *J. Am. Chem. Soc. 137*, 10554–10562.
(16) Padilla, J. E., Colovos, C., and Yeates, T. O. (2001) Nanohedra: using symmetry to design self assembling protein cages, layers, crystals, and filaments. *Proc. Natl. Acad. Sci. U. S. A. 98*, 2217–2221.
(17) King, N. P., Sheffler, W., Sawaya, M. R., Vollmar, B. S., Sumida, J. P., André, I., Gonen, T., Yeates, T. O., and Baker, D. (2012) Computational design of self-assembling protein nanomaterials with atomic level accuracy. *Science 336*, 1171–1174.
(18) Lai, Y.-T., Hura, G. L., Dyer, K. N., Tang, H. Y. H., Tainer, J. A., and Yeates, T. O. (2016) Designing and defining dynamic protein cage nanoassemblies in solution. *Sci. Adv. 2*, e1501855.
(19) Fallas, J. A., and Hartgerink, J. D. (2012) Computational design of self-assembling register-specific collagen heterotrimers. *Nat. Commun. 3*, 1087–1088.
(20) King, N. P., Bale, J. B., Sheffler, W., McNamara, D. E., Gonen, S., Gonen, T., Yeates, T. O., and Baker, D. (2014) Accurate design of co-assembling multi-component protein nanomaterials. *Nature 510*, 103–108.

(21) Bale, J. B., Gonen, S., Liu, Y., Sheffler, W., Ellis, D., Thomas, C., Cascio, D., Yeates, T. O., Gonen, T., King, N. P., and Baker, D. (2016) Accurate design of megadalton-scale two-component icosahedral protein complexes. *Science 353*, 389–394.

(22) Leaver-Fay, A., Tyka, M., Lewis, S. M., Lange, O. F., Thompson, J., Jacak, R., Kaufman, K., Renfrew, P. D., Smith, C. A., Sheffler, W., Davis, I. W., Cooper, S., Treuille, A., Mandell, D. J., Richter, F., Ban, Y. E. A., Fleishman, S. J., Corn, J. E., Kim, D. E., Lyskov, S., Berrondo, M., Mentzer, S., Popović, Z., Havranek, J. J., Karanicolas, J., Das, R., Meiler, J., Kortemme, T., Gray, J. J., Kuhlman, B., Baker, D., and Bradley, P. (2011) Rosetta3: An object-oriented software suite for the simulation and design of macromolecules. *Methods Enzymol. 487*, 545–574.

(23) Kramer, M. A., Wetzel, S. K., Plückthun, A., Mittl, P. R. E., and Grütter, M. G. (2010) Structural determinants for improved stability of designed ankyrin repeat proteins with a redesigned C-capping module. *J. Mol. Biol. 404*, 381–91.

(24) Rämisch, S., Weininger, U., Martinsson, J., Akke, M., and André, I. (2014) Computational design of a leucine-rich repeat protein with a predefined geometry. *Proc. Natl. Acad. Sci. U. S. A. 111*, 17875–17880.

(25) Doyle, L., Hallinan, J., Bolduc, J., Parmeggiani, F., Baker, D., Stoddard, B. L., and Bradley, P. (2015) Rational design of α-helical tandem repeat proteins with closed architectures. *Nature 528*, 585–588.

(26) Huang, P.-S., Oberdorfer, G., Xu, C., Pei, X. Y., Nannenga, B. L., Rogers, J. M., DiMaio, F., Gonen, T., Luisi, B., and Baker, D. (2014) High thermodynamic stability of parametrically designed helical bundles. *Science 346*, 481–485.

(27) Zheng, J., Birktoft, J. J., Chen, Y., Wang, T., Sha, R., Constantinou, P. E., Ginell, S. L., Mao, C., and Seeman, N. C. (2009) From molecular to macroscopic via the rational design of a self-assembled 3D DNA crystal. *Nature 461*, 74–77.

(28) Kočar, V., Schreck, J. S., Čeru, S., Gradišar, H., Bašić, N., Pisanski, T., Doye, J. P. K., and Jerala, R. (2016) Design principles for rapid folding of knotted DNA nanostructures. *Nat. Commun. 7*, 71083.

(29) Lupas, A. (1996) Coiled coils: New structures and new functions. *Trends Biochem. Sci. 21*, 375–382.

(30) Liu, J., and Rost, B. (2001) Comparing function and structure between entire proteomes. *Protein Sci. 10*, 1970–1979.

(31) Gradišar, H., and Jerala, R. (2014) Self-assembled bionanostructures: Proteins following the lead of DNA nanostructures. *J. Nanobiotechnology 12*, 1–9.

(32) Gradišar, H., Božič, S., Doles, T., Vengust, D., Hafner-Bratkovič, I., Mertelj, A., Webb, B., Šali, A., Klavžar, S., and Jerala, R. (2013) Design of a single-chain polypeptide tetrahedron assembled from coiled-coil segments. *Nat. Chem. Biol. 9*, 362–366.

(33) Ljubetič, A., Lapenta, F., Gradišar, H., Drobnak, I., Aupič, J., Strmšek, Ž., Lainšček, D., Hafner-Bratkovič, I., Majerle, A., Krivec, N., Benčina, M., Pisanski, T., Veličković, T. Ć., Round, A., Carazo, J. M., Melero, R., and Jerala, R. (2017) Design of coiled-coil protein-origami cages that self-assemble in vitro and in vivo. *Nat. Biotechnol. 35*, 1094–1101.

(34) Drobnak, I., Gradišar, H., Ljubetič, A., Merljak, E., and Jerala, R. (2017) Modulation of Coiled-Coil Dimer Stability through Surface Residues while Preserving Pairing Specificity. *J. Am. Chem. Soc. 139*, 8229–8236.

(35) Sontz, P. A., Song, W. J., and Tezcan, F. A. (2014) Interfacial metal coordination in engineered protein and peptide assemblies. *Curr. Opin. Chem. Biol. 19*, 42–49.

(36) Salgado, E. N., Ambroggio, X. I., Brodin, J. D., Lewis, R. A., Kuhlman, B., and Tezcan, F. A. (2010) Metal templated design of protein interfaces. *Proc. Natl. Acad. Sci. U. S. A. 107*, 1827–1832.
(37) Aupič, J., Lapenta, F., and Jerala, R. (2018) SwitCCh: Metal-site design for controlling the assembly of a coiled-coil homodimer. *ChemBioChem 19*, 2453–2457.
(38) Bellapadrona, G., and Elbaum, M. (2016) Design of a Redox-Sensitive Supramolecular Protein Assembly System Operating in Live Cells. *Nano Lett. 16*, 6231–6235.
(39) Stakkestad, O., Lyngstadaas, S. P., Thiede, B., Vondrasek, J., Skålhegg, B. S., and Reseland, J. E. (2017) Phosphorylation modulates ameloblastin self-assembly and Ca2+binding. *Front. Physiol. 8*, 1–10.
(40) Webber, M. I., Newcomb, C. J., Bitton, R., and Stupp, S. I. (2011) Switching of Self-Assembly in a Peptide Nanostructure with a Specific Enzyme. *Soft Matter 7*, 9665–9672.
(41) Lin, Y. A., Ou, Y. C., Cheetham, A. G., and Cui, H. (2014) Rational design of MMP degradable peptide-based supramolecular filaments. *Biomacromolecules 15*, 1419–1427.
(42) Shekhawat, S. S., Porter, J. R., Sriprasad, A., and Ghosh, I. (2009) An Autoinhibited Coiled-Coil Design Strategy for Split-Protein Protease Sensors. *J. Am. Chem. Soc. 131*, 15284–15290.
(43) Camacho-Soto, K., Castillo-Montoya, J., Tye, B., Ogunleye, L. O., and Ghosh, I. (2014) Small Molecule Gated Split-Tyrosine Phosphatases and Orthogonal Split-Tyrosine Kinases. *J. Am. Chem. Soc. 136*, 17078–17086.
(44) MacEwan, S. R., and Chilkoti, A. (2014) Applications of elastin-like polypeptides in drug delivery. *J Control Release 190*, 314–330.
(45) Uversky, V. N., Gillespie, J. R., Millett, I. S., Khodyakova, A. V., Vasiliev, A. M., Chernovskaya, T. V., Vasilenko, R. N., Kozlovskaya, G. D., Dolgikh, D. A., Fink, A. L., Doniach, S., and Abramov, V. M. (1999) Natively unfolded human prothymosin α adopts partially folded collapsed conformation at acidic pH. *Biochemistry 38*, 15009–15016.
(46) Nizard, P., Liger, D., Gaillard, C., and Gillet, D. (1998) Anchoring antibodies to membranes using a diphtheria toxin T domain-ZZ fusion protein as a pH sensitive membrane anchor. *FEBS Lett. 433*, 83–88.
(47) Vargo, K. B., Parthasarathy, R., and Hammer, D. A. (2012) Self-assembly of tunable protein suprastructures from recombinant oleosin. *Proc. Natl. Acad. Sci. U. S. A. 109*, 11657–11662.
(48) Mahler, A., Reches, M., Rechter, M., Cohen, S., and Gazit, E. (2006) Rigid, self-assembled hydrogel composed of a modified aromatic dipeptide. *Adv. Mater. 18*, 1365–1370.
(49) Fu, J., Guerette, P. A., and Miserez, A. (2015) Self-Assembly of Recombinant Hagfish Thread Keratins Amenable to a Strain-Induced α-Helix to β-Sheet Transition. *Biomacromolecules 16*, 2327–2339.
(50) Hoersch, D., Roh, S.-H., Chiu, W., and Kortemme, T. (2013) Reprogramming an ATP-driven protein machine into a light-gated nanocage. *Nat Nanotechnol. 8*, 928–932.
(51) Pudasaini, A., El-Arab, K. K., and Zoltowski, B. D. (2015) LOV-based optogenetic devices: light-driven modules to impart photoregulated control of cellular signaling. *Front. Mol. Biosci. 2*, 1–15.
(52) Duan, L., Che, D., Zhang, K., Ong, Q., Guo, S., and Cui, B. (2015) Optogenetic control of molecular motors and organelle distributions in cells. *Chem Biol. 22*, 671–682.
(53) Reynhout, I. C., Cornelissen, J. J. L. M., and Nolte, R. J. M. (2009) Synthesis of Polymer - Biohybrids : From Small to Giant Surfactants. *Acc. Chem. Res. 42*, 681–692.

(54) Thomas, C. S., Xu, L., and Olsen, B. D. (2012) Kinetically controlled nanostructure formation in self-assembled globular protein-polymer diblock copolymers. *Biomacromolecules 13*, 2781–2792.
(55) Onoda, A., Ueya, Y., Sakamoto, T., Uematsu, T., and Hayashi, T. (2010) Supramolecular hemoprotein-gold nanoparticle conjugates. *Chem. Commun. 46*, 9107–9109.
(56) You, C., and Piehler, J. (2016) Functional protein micropatterning for drug design and discovery. *Expert Opin. Drug Discov. 11*, 105–119.
(57) Basu, S., Gerchman, Y., Collins, C. H., Arnold, F. H., and Weiss, R. (2005) A synthetic multicelular system for programmed pattern formation. *Nature 434*, 1130–1134.
(58) Kong, W., Blanchard, A. E., Liao, C., and Lu, T. (2017) Engineering robust and tunable spatial structures with synthetic gene circuits. *Nucleic Acids Res. 45*, 1005–1014.
(59) Liu, C., Fu, X., Liu, L., Ren, X., Chau, C., Li, S., Xiang, L., Zeng, H., Chen, G., Tang, L., Lenz, P., Cui, X., Huang, W., Hwa, T., and Huang, J. (2011) Sequential Establishment of Stripe Patterns in an Expanding Cell Population. *Science 334*, 238–241.
(60) Boehm, C. R., Grant, P. K., and Haseloff, J. (2018) Programmed hierarchical patterning of bacterial populations. *Nat. Commun. 9*, 1–10.
(61) Karig, D., Martini, K. M., Lu, T., DeLateur, N. A., Goldenfeld, N., and Weiss, R. (2018) Stochastic Turing patterns in a synthetic bacterial population. *Proc. Natl. Acad. Sci. 115*, 6572–6577.
(62) Tabor, J. J., Salis, H. M., Simpson, Z. B., Chevalier, A. A., Levskaya, A., Marcotte, E. M., Voigt, C. A., and Ellington, A. D. (2009) A Synthetic Genetic Edge Detection Program. *Cell 137*, 1272–1281.
(63) Tabor, J. J., Levskaya, A., and Voigt, C. A. (2011) Multichromatic control of gene expression in escherichia coli. *J. Mol. Biol. 405*, 315–324.
(64) Chen, F., and Wegner, S. V. (2017) Blue Light Switchable Bacterial Adhesion as a Key Step toward the Design of Biofilms. *ACS Synth. Biol. 6*, 2170–2174.
(65) Jin, X., and Riedel-Kruse, I. H. (2018) Biofilm Lithography enables high-resolution cell patterning via optogenetic adhesin expression. *Proc. Natl. Acad. Sci. U. S. A. 115*, 3698–3703.
(66) Pu, L., Yang, S., Xia, A., and Jin, F. (2018) Optogenetics Manipulation Enables Prevention of Biofilm Formation of Engineered Pseudomonas aeruginosa on Surfaces. *ACS Synth. Biol. 7*, 200–208.
(67) Huang, Y., Xia, A., Yang, G., and Jin, F. (2018) Bioprinting Living Biofilms through Optogenetic Manipulation. *ACS Synth. Biol. 7*, 1195–1200.
(68) Suo, Z., Avci, R., Yang, X., and Pascual, D. W. (2008) Efficient immobilization and patterning of live bacterial cells. *Langmuir 24*, 4161–4167.
(69) Palacios-Cuesta, M., Cortajarena, A. L., García, O., and Rodríguez-Hernández, J. (2015) Patterning of individual Staphylococcus aureus bacteria onto photogenerated polymeric surface structures. *Polym. Chem. 6*, 2677–2684.
(70) Velema, W. A., Van Der Berg, J. P., Szymanski, W., Driessen, A. J. M., and Feringa, B. L. (2015) Bacterial patterning controlled by light exposure. *Org. Biomol. Chem. 13*, 1639–1642.
(71) Connell, J. L., Ritschdorff, E. T., Whiteley, M., and Shear, J. B. (2013) 3D printing of microscopic bacterial communities. *Proc. Natl. Acad. Sci. U. S. A. 110*, 18380–18385.

(72) Xu, L., Robert, L., Ouyang, Q., Taddei, F., Chen, Y., Lindner, A. B., and Baigl, D. (2007) Microcontact printing of living bacteria arrays with cellular resolution. *Nano Lett. 7*, 2068–2072.
(73) Eun, Y. J., and Weibel, D. B. (2009) Fabrication of microbial biofilm arrays by geometric control of cell adhesion. *Langmuir 25*, 4643–4654.
(74) Xu, T., Petridou, S., Lee, E. H., Roth, E. A., Vyavahare, N. R., Hickman, J. J., and Boland, T. (2004) Construction of High-Density Bacterial Colony Arrays and Patterns by the Ink-Jet Method. *Biotechnol. Bioeng. 85*, 29–33.
(75) Zheng, Q., Lu, J., Chen, H., Huang, L., Cai, J., and Xu, Z. (2011) Application of inkjet printing technique for biological material delivery and antimicrobial assays. *Anal. Biochem. 410*, 171–176.
(76) Lehner, B. A. E., Schmieden, D. T., and Meyer, A. S. (2017) A Straightforward Approach for 3D Bacterial Printing. *ACS Synth. Biol. 6*, 1124–1130.
(77) Schaffner, M., Rühs, P. A., Coulter, F., Kilcher, S., and Studart, A. R. (2017) 3D printing of bacteria into functional complex materials. *Sci. Adv. 3*, eaao6804.
(78) Schmieden, D. T., Basalo Vázquez, S. J., Sangüesa, H., Van Der Does, M., Idema, T., and Meyer, A. S. (2018) Printing of Patterned, Engineered E. coli Biofilms with a Low-Cost 3D Printer. *ACS Synth. Biol. 7*, 1328–1337.
(79) Huang, J., Liu, S., Zhang, C., Wang, X., Pu, J., Ba, F., Xue, S., Ye, H., Zhao, T., Li, K., Wang, Y., Zhang, J., Wang, L., Fan, C., Lu, T. K., and Zhong, C. (2018) Programmable and printable Bacillus subtilis biofilms as engineered living materials. *Nat. Chem. Biol.* doi: 10.1038/s41589-018-0169-2.
(80) Joshi, S., Cook, E., and Mannoor, M. S. (2018) Bacterial Nanobionics via 3D Printing. *Nano Lett.* 10.1021/acs.nanolett.8b02642.
(81) Mitragotri, S., Anderson, D. G., Chen, X., Chow, E. K., Ho, D., Kabanov, A. V., Karp, J. M., Kataoka, K., Mirkin, C. A., Petrosko, S. H., Shi, J., Stevens, M. M., Sun, S., Teoh, S., Venkatraman, S. S., Xia, Y., Wang, S., Gu, Z., and Xu, C. (2015) Accelerating the Translation of Nanomaterials in Biomedicine. *ACS Nano 9*, 6644–6654.
(82) Qi, G. Bin, Gao, Y. J., Wang, L., and Wang, H. (2018) Self-Assembled Peptide-Based Nanomaterials for Biomedical Imaging and Therapy. *Adv. Mater. 30*, e1703444.
(83) Lee, E. J., Lee, N. K., and Kim, I. S. (2016) Bioengineered protein-based nanocage for drug delivery. *Adv. Drug Deliv. Rev. 106*, 157–171.
(84) Karch CP, and Burkhard, P. (2016) Vaccine Technologies: From Whole Organisms to rationally Designed Protein Assemblies *120*, 1–14.
(85) Daniel J. Smith, Gabriel A. Brat, Scott H. Medina, Dedi Tong, Yong Huang, Johanna Grahammer, Georg J. Furtmüller, Byoung Chol Oh, Katelyn J. Nagy-Smith, P., and Walczak, Gerald Brandacher, and J. P. S. (2015) A multi-phase transitioning peptide hydrogel for suturing ultra- small vessels *11*, 37–54.
(86) De Santis, E., Alkassem, H., Lamarre, B., Faruqui, N., Bella, A., Noble, J. E., Micale, N., Ray, S., Burns, J. R., Yon, A. R., Hoogenboom, B. W., and Ryadnov, M. G. (2017) Antimicrobial peptide capsids of de novo design. *Nat. Commun. 8*, 2263.
(87) Hernandez-Garcia, A., Kraft, D. J., Janssen, A. F. J., Bomans, P. H. H., Sommerdijk, N. A. J. M., Thies-Weesie, D. M. E., Favretto, M. E., Brock, R., De Wolf, F. A., Werten, M. W. T., Van Der Schoot, P., Stuart, M. C., and De Vries, R. (2014) Design and self-assembly of simple coat proteins for artificial viruses. *Nat. Nanotechnol. 9*, 698–702.

(88) Liu, J., Hou, C., Luo, Q., Liu, J., Miao, L., Zhang, C., Gao, Y., Zhang, X., Xu, J., and Dong, Z. (2012) Construction of GPx active centers on natural protein nanodisk/nanotube: A new way to develop artificial nanoenzyme. *ACS Nano 6*, 8692–8701.

(89) Sasso, L., Suei, S., Domigan, L., Healy, J., Nock, V., Williams, M. A. K., and Gerrard, J. A. (2014) Versatile multi-functionalization of protein nanofibrils for biosensor applications. *Nanoscale 6*, 1629–1634.

(90) Majithia, R., Patterson, J., Bondos, S. E., and Meissner, K. E. (2011) On the design of composite protein-quantum dot biomaterials via self-assembly. *Biomacromolecules 12*, 3629–3637.

(91) Omichi, M., Asano, A., Tsukuda, S., Takano, K., Sugimoto, M., Saeki, A., Sakamaki, D., Onoda, A., Hayashi, T., and Seki, S. (2014) particle nano-fabrication technique. *Nat. Commun. 5*, 1–8.

(92) Knowles, T. P. J., Oppenheim, T. W., Buell, A. K., Chirgadze, D. Y., and Welland, M. E. (2010) Nanostructured films from hierarchical self-assembly of amyloidogenic proteins. *Nat. Nanotechnol. 5*, 204–207.

(93) Hollingshead, S., Lin, C. Y., and Liu, J. C. (2017) Designing Smart Materials with Recombinant Proteins. *Macromol. Biosci. 17*, 1–18.

(94) Guven, S., Chen, P., Inci, F., Tasoglu, S., Erkmen, B., and Demirci, U. (2015) Multiscale assembly for tissue engineering and regenerative medicine. *Trends Biotechnol. 33*, 269–279.

(95) Loose, M., Fischer-Friedrich, E., Ries, J., Kruse, K., and Schwille, P. (2008) Spatial regulators for bacterial cell division self-organize into surface waves in vitro. *Science 320*, 789–92.

(96) Gurdon, J. B., and Bourillot, P.-Y. (2001) Morphogen gradient interpretation. *Nature 413*, 797–803.

(97) Tasoglu, S., Yu, C. H., Liaudanskaya, V., Guven, S., Migliaresi, C., and Demirci, U. (2015) Magnetic Levitational Assembly for Living Material Fabrication. *Adv Heal. Mater. 4*, 1469–1476.

(98) Türker, E., Demirçak, N., and Arslan-Yildiz, A. (2018) Scaffold-free three-dimensional cell culturing using magnetic levitation. *Biomater. Sci. 6*, 1745–1753.

(99) Xu, F., Finley, T. D., Turkaydin, M., Sung, Y., Gurkan, U. A., Yavuz, A. S., Guldiken, R. O., and Demirci, U. (2011) The assembly of cell-encapsulating microscale hydrogels using acoustic waves. *Biomaterials 32*, 7847–7855.

(100) Eng, G., Lee, B. W., Parsa, H., Chin, C. D., Schneider, J., Linkov, G., Sia, S. K., and Vunjak-Novakovic, G. (2013) Assembly of complex cell microenvironments using geometrically docked hydrogel shapes. *Proc. Natl. Acad. Sci. U. S. A. 110*, 4551–4556.

(101) Chen, P., Luo, Z., Güven, S., Tasoglu, S., Ganesan, A. V., Weng, A., and Demirci, U. (2014) Microscale assembly directed by liquid-based template. *Adv. Mater. 26*, 5936–5941.

(102) Gopinathan, J., and Noh, I. (2018) Recent trends in bioinks for 3D printing. *Biomater. Res. 22*, 1–15.

(103) Toda, S., Blauch, L. R., Tang, S. K. Y., Morsut, L., and Lim, W. A. (2018) Programming self-organizing multicellular structures with synthetic cell-cell signaling. *Science 361*, 156–162.

(104) Liu, J. S., and Gartner, Z. J. (2012) Directing the assembly of spatially organized multicomponent tissues from the bottom up. *Trends Cell Biol. 22*, 683–691.

(105) Ren, H., Zhu, S., and Zheng, G. (2019) Nanoreactor Design Based on Self-Assembling Protein Nanocages. *Int. J. Mol. Sci. 20*, 592.

(106) Yan, M., Du, J., Gu, Z., Liang, M., Hu, Y., Zhang, W., Priceman, S., Wu, L., Zhou, Z. H., Liu, Z., Segura, T., Tang, Y.,

and Lu, Y. (2010) A novel intracellular protein delivery platform based on single-protein nanocapsules. *Nat. Nanotechnol. 5*, 48–53.

(107) Chevalier, A., Silva, D. A., Rocklin, G. J., Hicks, D. R., Vergara, R., Murapa, P., Bernard, S. M., Zhang, L., Lam, K. H., Yao, G., Bahl, C. D., Miyashita, S. I., Goreshnik, I., Fuller, J. T., Koday, M. T., Jenkins, C. M., Colvin, T., Carter, L., Bohn, A., Bryan, C. M., Fernández-Velasco, D. A., Stewart, L., Dong, M., Huang, X., Jin, R., Wilson, I. A., Fuller, D. H., and Baker, D. (2017) Massively parallel de novo protein design for targeted therapeutics. *Nature 550*, 74–79.

For Table of contents use only: