Advanced Research + Invention Agency ARIA

Universal Fabricator v1 – scalable production of programmable hierarchical nanocomposites

Programme Thesis

v0.1

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CONTEXT

This document presents the core thesis of a programme that is currently in development at ARIA, derived from the *Opportunity Space: Manufacturing Abundance*. We invite you to provide feedback to help us refine our thinking.

This is not a funding opportunity, but in most cases will lead to one – sign up **here** to learn about any funding opportunities derived or adapted from this programme thesis. ***Pending approval, we aim to launch an initial ~£50 M programme funding call in January 2026.***

An ARIA programme seeks to unlock a scientific or technical capability that

+ changes the perception of what's possible or valuable
+ has the potential to catalyse massive social and economic returns
+ is unlikely to be achieved without ARIA's intervention.

PROGRAMME THESIS, SIMPLY STATED

Stone, Bronze, Iron: ages of human history are defined by materials that transformed societies and mark breakthroughs in mastery over matter. Today's tools and techniques limit us to a tiny corner of the total possible materials design space, as well as a materials scale-up problem: a multi-decadal lag between the lab discovery of a new material class to its productisation. This programme will build platforms to discover processes that scalably produce hierarchical nanocomposites, which we believe will unlock a practically universal range of functional products. This will define our next age not by a single material, but by our ability to solve numerous bespoke problems by manufacturing abundant new materials.

PROGRAMME THESIS, EXPLAINED

Why this programme?

Foundational materials: are materials and material systems so impactful that they become a primary physical building block of civilisation at a planetary scale, that industries are built from or with. These are bulk materials (steel, cement, single-crystal silicon), chemicals (ammonia, chlorine, polymers), and material systems (Lithium-ion batteries, optical fibre).

What changed the world was not the discovery of these materials, but rather the development of processes that made them so cheap and abundant that it fundamentally reshaped the global economy.

Foundational material processes: mass produce a new chemical composition, internal structure, and/or complex system assembly, that enables new multi-trillion-£ industries, revolutionises global supply chains, and drastically alters the course of civilisation (**Fig. 1**).

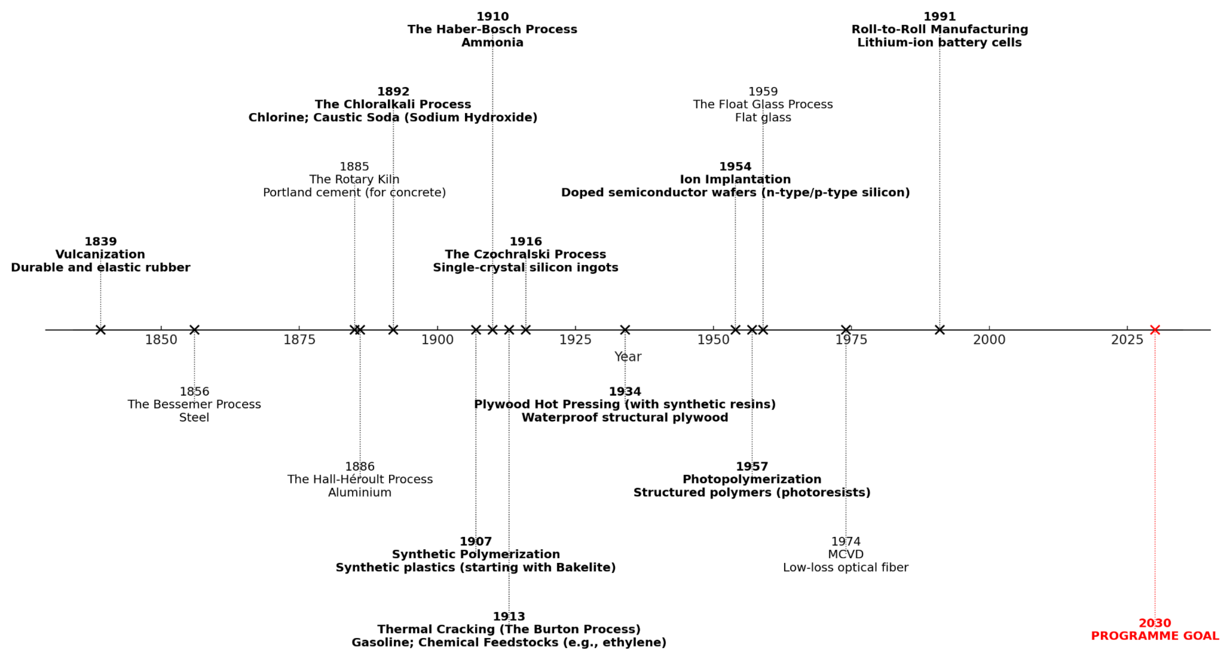

Fig. 1: Timeline of foundational materials processes discovered in modern history.[1] Regular font: mass production of a single foundational material. **Bold font:** platforms that scaled a class of many materials.

[1] Many world-changing process innovations were excluded if, rather than unlocking a new foundational material, they: **(1)** assembled/externally shaped a product (*e.g.,* the Assembly Line, transistors, additive manufacturing), **(2)** enhanced existing material properties (*e.g.,* metal cold working), **(3)** mass produced a high-value but specialized product / additive (*e.g.,* synthetic dyes, diamonds, insulin), and **(4)** optimised an existing process (*e.g.,* EUV Lithography, Fiberglass mass production).

Since 1800 there have only been 15 foundational material processes and since 1975 there has only been 1, marking a half century of stagnation. An intervention is needed to catalyse the development of new foundational materials processes. From 1930, there are 2 trends:

1. <u>Chemical-driven performance → Structure-driven performance</u>: The grand challenge of the 21st century is no longer discovering new chemistries, but mastering techniques to arrange existing chemistries into radically functional architectures.
2. <u>Materials → Material systems:</u> The emerging paradigm is the creation of multi-material assemblies (*e.g.,* batteries, optical fibers), precisely structured to create a functional unit with bulk properties (*e.g.,* energy density, attenuation coefficient).

We expect these trends to continue, with advancing robotics and spatiotemporally precise scientific hardware for materials characterisation and structural manipulation, from microfluidics to additive manufacturing. Advances in manipulating light, acoustics, magnetics and water, are particularly exciting as alternative phase change triggers to temperature and pressure that dominate the current 15 foundational material processes. Exponentially improving artificial intelligence (AI) means we can also now finally predict and design complex systems. If abundant, quality data is generated, early successes in proteins and inorganic crystals today are just a sample of what could be achieved.

Foundational material processes can come in waves, the most recent two were around petrochemicals and silicon. We believe we are at the confluence of two new big waves on the horizon, that an ARIA programme could radically accelerate and amplify:

1. **<u>Biology</u> is existence proof that we can sustainably transform flexible, locally available inputs into programmable outputs that access a significantly expanded material design space.** For example, from only oceanic building blocks that cover >70% of our planet, biology can manufacture all 11 of today's essential (>£100 B market-valued) material functions (energetic, magnetic, electronic, thermal, bioactive, optical, electrochemical, barrier, surface, structural, and catalytic). With advancing ability to engineer biology (as well as biomimetic polymer and supramolecular chemistry) we will soon have infinite libraries of designer molecules that we should be able to programmably assemble into systems.
2. <u>Clean energy (*e.g.,* solar)</u> is already cheap and will only get cheaper (*e.g.,* fusion). Substantially more energy will be generated, which will unlock carbon-free, high energy manufacturing approaches not previously possible.

What we hope to achieve

Conventionally, researchers have built platforms to discover new materials within a target design space. **This programme will fund teams to build platforms that investigate a design space of *processes* that can mass produce <u>hierarchical nanocomposites</u>:** materials and metamaterials with statistically robust, structure-driven performance. Their primary function (*e.g.*, mechanical, thermal, magnetic, chemical), emerges from internal architecture that is anisotropically ordered across multiple length scales (nano-to-centimetre), but not necessarily perfect (**Fig. 2**).

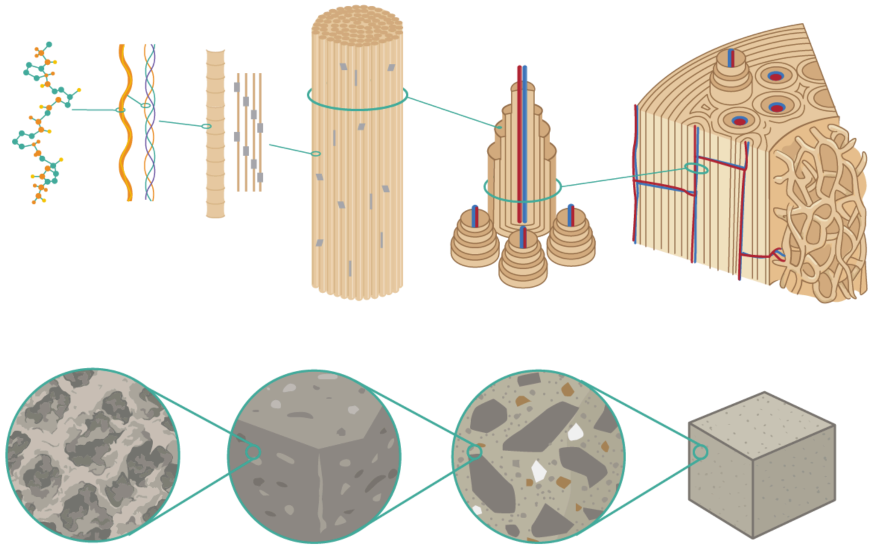

Fig. 2: (Top) Bone, a multi-length scaled, anisotropic, gradient structured hierarchical nanocomposite. (Bottom) Concrete, fewer levels of mostly homogeneous and isotropic defined structure.

Table 1: Example materials that teams could target. A table with more technical details can be found in **Appendix 1**.

Hierarchical nanocomposites	Why they are valuable
Synthetic wood to displace high-grade timber and composites	100x faster than growing a tree, for on-demand & carbon-negative construction
Precious metal free electrocatalysts to displace platinum and iridium catalysts	1000x cheaper, unlocking the green hydrogen economy
Passively adaptive thermal skins to displace todays insulation & HVAC systems	>100x reduced lifetime energy, enabling zero-energy buildings and smart textiles
Rare-earth-free permanent magnets to displace magnets reliant on rare-earths	>100x scalability and supply chain security, accelerating widespread electrification
Selective molecular sieve membranes to displace energy-intensive distillation	>100x energy-efficient selectivity creates new industries in molecular mining, carbon capture, and ultra-pure chemical processing
Structural supercapacitors to displace separate structural chasses and batteries	New paradigm of 'massless' energy storage for >100x ultra-lightweight electric transport

The range of examples above highlights our belief this platform could design processes that mass produce solutions for a '*practically universal*' range of extremely distinct functional applications, without needing the capability to manufacture a '*technically universal*' range of stable atomic arrangements (*i.e.,* atomically precise manufacturing). We believe that a portfolio of hardware (hybrid reactor-printers) and software (digital twins & design) capable of discovering and developing processes for programmable hierarchical nanocomposite materials and metamaterials, is a v1 '***Universal Fabricator***'.

Our vision for long-term impact

For all the advances in the digital world, our physical world is still dominated by ancient materials (wood, wool, glass), and antiquated ones (concrete, steel, plastic) built using a paradigm of brute-force heat and pressure: smelting, refining, cracking. Our continued reliance on manufacturing paradigms from the Iron Age (1200 BC) and 1900's chemical engineering have trapped us in complex supply chains and large-scale infrastructure that are dirty energy intensive, inherently brittle and inflexible. Elevated switching costs have systematically stifled materials innovation and have driven 3 core problems:

1. **No radically new materials**: we only have process and property data for a tiny corner of the total possible materials design space. Our manufacturing capabilities further limit us to an even tinier corner of that corner.
2. **Scale-up:** recent history shows a multi-decadal lag between the lab discovery of a new material class to its productisation, as new materials must be compatible with "scaled-up" infrastructure and have slow, expensive prototyping, if at all.
3. **Planetary health crises and global conflicts**: we fight over scarce natural resources, distributed through complex, brittle global supply chains. To conserve using expensive, dirty energy we waste excess matter, irreversibly converting it into environmental pollution.

In the longer term, **scaling-out** the *Universal Fabricator v1* from a process discovery platform to parallelised, flexible, high-volume production will move us to a future where radially new materials are sustainably produced at scale for every day use:

1. **Generatively designed materials for very custom, specific functions**: experimental process-structure-property data generation and rapid prototyping will enable AI exploration into totally new design spaces. This will make designing physical materials as intuitive and creative as programming software today, leading to a Cambrian explosion of new materials that will transform how we build everything:
    + **Radical Multifunctionality**: Instead of assembling multiple materials, we can create single, continuous material systems with integrated functions. This leads to lighter, simpler, and more robust systems by eliminating the points of failure that often occur at the interface between separate materials.

    + **Active Systems**: hierarchical nanocomposites are an essential prerequisite passive "chassis" that translates nano-scale activity into coordinated, macroscopic function, paving the way for future morphing and dynamic systems that adaptively respond to their environment

2. **Scaled-out mass production**: we will make things exactly where and when we need them: imagine a world where intricate structures are grown on-site. We will move from a system where production systems will be flexible and robust to taking in adapting abundant inputs, to produce a broad range of outputs.
3. **Sustainable Abundance**: we won't have to produce a single item more than we need. Resilient local manufacturing capabilities will finally make the inefficient and polluting paradigms of the Iron Age and petrochemicals obsolete, eliminating brittle global supply chains and ending resource conflicts. Abundant clean energy will be maximally leveraged to make fully circular matter the convenient, economic default. The introduction of new foundational materials changes societies. Plastics introduced single-use culture. The next foundational materials will introduce a perennial materials culture of adaptation and circularity.

Why ARIA?

+ **Industry** will prioritise funding innovations that fit into existing infrastructure and paradigms. For example, manufacturing and biomanufacturing are completely siloed
    → In this programme ARIA will only fund the development of processes that make existing scaled-up infrastructure obsolete, and have a strong preference to fund at the interface of biotic and abiotic manufacturing systems
+ **Private capital** will fund startups to sprint towards profitability, which requires scaling within existing infrastructure and strongly incentivises niche, low-volume, high-market-value products *e.g.,* small molecules, therapeutics, and catalysts
    → In this programme ARIA will only fund the development of processes that specifically target high-volume foundational materials
+ **Public funding** will fund academic-industrial collaborations, projects with total creative freedom, and projects with capped risk via committee vetting
    → In this programme ARIA will fund tightly integrated interdisciplinary teams of scientists and engineers who believe a radical systemic overhaul is possible, regardless of their location, institution, career-stage and publication record, to work towards a highly focused goal with an expected ~1% success rate

POTENTIAL PROGRAMME STRUCTURE

The following represents our current thinking on a potential programme structure. We are actively seeking feedback on how to structure the programme, creator teams, and metrics.

What we expect to fund, at a high level

This programme succeeds if within 5 years: we have built the first end-to-end prototype of the *Universal Fabricator* v1 platform, and operated it to produce at least 1 likely future foundational material, which achieves pre-defined key performance metrics that are a >100x improvement over the state-of-the-art it displaces, at meaningful length and time scales.

As part of programme success, we expect to establish a shared open data ecosystem for hierarchical nanocomposite processes, based on standardised process-structure-property data and metadata obtained by teams across a large number of production runs. Our current thinking on IP and open-sourcing can be found under **Questions we still have**.

We are not expecting within 5 years: fully scaled production nor a commercially viable product. We do expect derisking sufficiently to raise substantial private capital during or after the programme to translate the platform, material and/or a material enabled product.

We anticipate funding a variety of 'creators': startups, frontier research organisations and contractors, academic research groups, independent individuals, and integrated teams of the above — to tackle the various challenges from multiple angles, and to plant the seeds for a lasting collaborative ecosystem in materials process discovery and development.

Funding will be allocated in 3 phases:

+ Pending approval, an initial ~£50 M will be allocated from ARIA across teams over 2 phases (~3.5 years) en route towards achieving the overall programme goal.
+ Drawing inspiration from a 'Seed round' and 'Series A' funding model, teams that hit pre-agreed milestones will be eligible for subsequent phase funding. Given the expected low success rate of any single approach, to increase the success probability of the overall programme by dynamic allocation of funds, follow-on funding for any single creator is not guaranteed.
+ That said, there is no pre-set number of teams per phase; teams are not competing against one another. Rather they should collaborate to compete for investment with existing materials manufacturing. Teams may be merged/restructured at the end of phases to allocate efforts and resources towards the most promising platforms.
+ If at least 1 creator team is successful at achieving their end of Phase 2 milestones, in a final Phase 3 (~1.5 years), ARIA will allocate a minimum additional ~£10 M with potentially additional co-raised private capital.

Technical Areas (TAs)

Programme success will require both deep expert knowledge and systematic integration of know-how from a number of fields that could span: material science, chemical engineering, engineering biology, chemistry, condensed matter physics, computer science, mechanical engineering, electrical engineering, architecture and more. The key will be robust implementation of novel hardware, software, supply chains and analytics. In Phases 1-2 of the programme, we expect to initially fund ***integrated platform*** *teams* to solve challenges across four technical areas, ***specialist*** *teams or individuals* to potentially work on only one or two areas, and ***ecosystem*** *teams or individuals* to provide support across multiple teams.

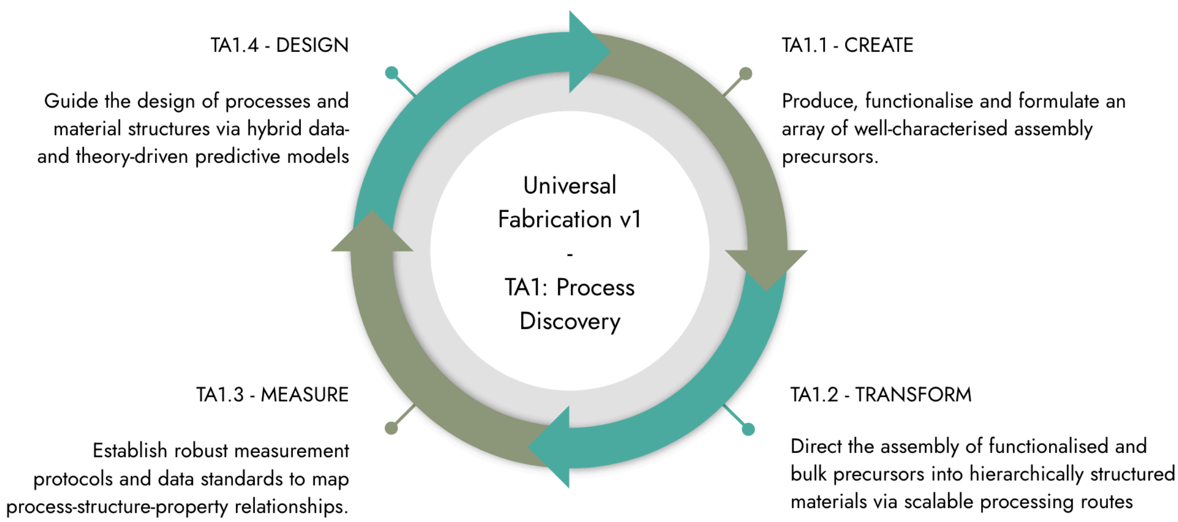

Fig. 3: The self-reinforcing feedback loop of the integrated process discovery platform. Innovation, collaboration, and standardisation across all technical areas and creators will enable the rapid industrialisation of a vast array of hierarchical nanocomposite materials.

TA1.1: Create – Production of a library of functionalised assembly precursors

Many hierarchical nanocomposites are assembled in multi-stage, multi-lengthscale processes. Although the final stage is often rapid and irreversible, intermediate stages often rely on carefully controlled, slower, and reversible self-assembly processes, and the nano-scale compartmentalisation of process intermediates.

Although incredible advances are being made in industrial scale uses of liquid-liquid phase separation and encapsulation of active ingredients, such as the case of lipid nanoparticle formulation for mRNA vaccines, we lack a generalizable method to reliably create and stabilize a wide diversity of functionalized nanoscale intermediates, particularly for complex multi-component systems intended for subsequent directed assembly.

Another challenge is our lack of established structure- and property-based separation methods for nanoscale structured materials. To combat these issues, we either need to further understand and develop such methods, or, in a more bioinspired manner, incorporate error correction mechanisms, such as redundancy and kinetic proof-reading, into the production process itself.

These stable **functionalised assembly precursors** may contain mixtures of a small fraction of programmable, information-rich and "bulk" components, that could be biotic and/or abiotic, such as proteins, nucleic acids, lipids, polymers, inorganic nanoparticles, metal ions and other small additives. We expect the created liquids, suspensions, slurries and powders to be used as inputs for the creation of macroscopic structured materials.

TA1.2: Transform – Control of assembly and phase transitions in structured nanomaterials

This technical area represents the critical execution stage of the manufacturing process, where stable functionalised assembly precursors are transformed into the functional hierarchical material. We draw an aspirational analogy to plastic extrusion / injection moulding: a highly mature process that rapidly and reliably transforms simple precursor pellets into a precisely shaped final product. Our goal is to develop a similarly robust and controllable 'moulding' process for hierarchical nanocomposite matter.

However, unlike injection moulding where the mould defines only the external shape and macroscopic cooling properties, here the 'process recipe' acts as a dynamic, four-dimensional mould that orchestrates the assembly of a material's internal hierarchical structure across multiple length scales. This is the heart of the programme's challenge.

Creators will design and implement the physical processes and hardware that execute these recipes. This involves more than simply triggering a phase transition; it requires precise, real-time control over the entire assembly pathway. We expect proposals to focus on:

+ Directed Self-Assembly: Developing methods to guide the thermodynamic process of self-assembly using external fields and controlled environmental changes. This includes the application of specific stimuli, including thermal gradients, pH or solvent shifts, photonic, magnetic, or acoustic fields, and controlled shear or flow conditions within novel reactor designs (*e.g.,* flow reactors, custom scaffolds).
+ Kinetic Control: Engineering processes that deliberately trap materials in useful, high-performance non-equilibrium states. For many advanced materials, the most valuable structures are metastable. A deep understanding of the kinetics of assembly is required to form and stabilize these structures reliably, preventing the system from relaxing into lower-performance equilibrium states.

+ Error Correction: similar to TA1.1, although we are not shooting for atomically precise materials, we want statistically robust materials with some degree of process-governed defect control (*e.g.*, redundancy, kinetic proof reading)

Success in this TA will be defined by the ability to develop a process that is not only effective but also repeatable, predictable, and ultimately, scalable. This TA bridges the gap between a library of potential building blocks[2] (from TA1.1) and a robust method for manufacturing functional, macro-scale hierarchical nanocomposites.

TA1.3: Measure — Development of analytical methods and data standards

The most sophisticated predictions and elegant processes are useless without the ability to rapidly and accurately measure what is actually happening. This TA will provide the critical feedback loops that enable learning, control, and validation across the programme. This is the foundation for turning material discovery from an art into a reproducible science.

Creators will characterise complex, multi-scale structures and the dynamic processes that form them. The emphasis is not on developing novel measurement techniques for their own sake, but on creating a coherent data pipeline that directly informs the work of other TAs. We expect proposals to focus on two key areas:

1. Process-Structure-Property Mapping: to guide discovery, we need to understand both the materials we are making and the processes that make them. This involves:
    + Structural and Functional Analysis: to systematically characterise the functionalised assembly precursors from TA1.1 and the hierarchical materials from TA1.2, via a suite of existing techniques (*e.g.,* electron microscopy, scattering, spectroscopy, mechanical testing) in a high-throughput manner to build a comprehensive picture of process outcomes.
    + In-Line Monitoring: to gain insight into the critical transformation stage in TA1.2 by monitoring key physical and chemical parameters during the assembly process. This could involve integrating sensors and analytical tools into process hardware to track changes both in macroscopic properties (*e.g.,* temperature, pressure, flow, or spectral signatures), and potentially in (bio-)chemical composition of material balances, providing the real-time data needed to understand and control the formation of the material's structure.
2. Standardising Data for Predictive Modelling: to enable quickly incorporating learnings from the programme across teams and later the wider community, we must:

[2] If feasible, teams may skip explicitly creating stable functionalised assembly precursors as building blocks, and develop a fully integrated process, generating the hierarchical nanocomposites from simple bulk materials and chemicals (*i.e.,* accomplish TA1.1 and 1.2 in 1 shot).

+ Develop Data Standards: establishing and implementing common protocols for how experiments are conducted, how data is measured, and how it is formatted and stored. This ensures that results from different teams are comparable and can be integrated into a single, high-value dataset.
+ Create Rich Datasets: fusing data from multiple characterisation techniques into a unified digital description of each material and process. This provides material and process design software with the rich, multi-modal data required to train and validate models that can accurately predict the relationships between process parameters, material structure, and final properties.

We expect that all data generated across TA1 (Programme Phases 1-2) to be findable, accessible, interoperable, and reusable (FAIR), thereby creating a lasting, high-value dataset for the entire materials community. Our current thinking on IP and open-sourcing can be found under **Questions we still have**.

TA1.4: Design — *In silico* design and data-driven prediction of hierarchical assembly process-structure-property relationships

Materials science, especially armed with recent AI-driven hybrid simulations and surrogate models, is full of wondrous predicted materials, which we cannot manufacture in practice due to the lack of reliable and scalable processes.

This technical area is dedicated to the development of a '**materials compiler**': a software platform for the in-silico design and prediction of novel hierarchical materials and their assembly processes. Creators will move beyond traditional materials discovery by focusing on the simulation of the entire process-structure-property chain. We expect proposals to incorporate physics-informed machine learning, multi-scale modeling, and generative design to navigate the vast parameter space of hierarchical material synthesis.

Key challenges include developing models that can accurately predict how precursor materials will assemble under different process conditions and how the resulting hierarchical structure will translate to macroscopic properties. We anticipate the use of techniques ranging from molecular dynamics to finite element analysis, integrated in a way that allows for a seamless flow of information between different length and time scales.

This TA will provide the foundational predictive power to guide the experimental and engineering work in the other TAs, and also benefit from continually incorporating the novel data generated from those, potentially in a Bayesian active learning manner to explore high expected value areas of the process space.

Who we are looking for

The team structures described are intended to guide proposals towards achieving the goals of the programme. ARIA welcomes proposals with alternative team structures, if we are convinced they have a higher likelihood of achieving the goals of the programme.

We will fund three classes of creators (individuals, organisations, and institutions who receive funding) in two technical workstreams (see **Table 2** for summary). All creators and workstreams share the same goal, but will utilise different inputs and expertise.

Table 2: Summary of creator types and technical workstreams

<table>
<tr><th colspan="2"></th><th colspan="2">Technical Workstreams</th></tr>
<tr><th colspan="2"></th><th>Living Systems</th><th>Synthetic Systems</th></tr>
<tr><td rowspan="6">Creator types</td><td rowspan="2">Integrated Platform</td><td colspan="2">Larger teams with hybrid approaches,
e.g. Living systems for precursor production and Synthetic systems for assembly</td></tr>
<tr><td>Teams with end-to-end cell/organism based approaches, including biological pathway modelling and extracellular matrix solidification experience</td><td>Teams with end-to-end cell-free approaches, including information encoded inputs, phase change methods, process simulation & digital design</td></tr>
<tr><td rowspan="2">Specialist</td><td colspan="2">Method development for encapsulation, functionalisation and formulation of assembly precursors,
Analytical method development for intermediate and final hierarchical materials</td></tr>
<tr><td>Synthetic / Cellular Biology,
Bioengineering & Bioprocessing,
Protein & Genetic Engineering,
Biological Hierarchical Materials</td><td>Nanomaterials & Polymer Chemistry,
Condensed Matter Physics & Chemical Engineering,
Rheology & Fluid Dynamics</td></tr>
<tr><td rowspan="2">Ecosystem Contributor</td><td colspan="2">Hardware/electrical engineering + automation,
Integrated software systems & open data infrastructure</td></tr>
<tr><td>Standardisation, production and analytics of biological precursors and final materials</td><td>Analytical characterisation of hierarchical materials,
Standardisation, production and analytics of abiotic precursors</td></tr>
</table>

We believe that hybrid, interdisciplinary platforms, implemented by agile, focused integrated single-organisation teams are most likely to achieve the ambitious goals of this programme (leveraging subcontracting for short-term expertise when needed). However, we understand that it may be difficult to form teams able to handle the added complexity during the initial application process. Therefore, we also encourage applications from cross-institutional collaborations with strong, clear leadership and internal management structure, as well as individuals and specialist teams. We will give strong preference to teams with the minimum complexity required to achieve the programme's goals. We expect to foster collaboration and merging of creators during the proposal stage and at Phase transition points during the programme.

How we expect to fund, in detail

Concept papers: we welcome high-level ideas from individuals, small teams, and fully formed teams. At this stage we will encourage the self assembly, and catalyse the directed assembly of individuals and small teams → *integrated platform* and *ecosystem* teams.

Full proposal:

+ We expect ***integrated platform*** teams to propose a target hierarchical nanocomposite and the integrated computational and physical platform they will build to explore the process space to produce it. Suitable process and performance metrics should also be proposed, which will be negotiated upfront and revisited at pre-agreed checkpoints during the programme.
+ **As a rudimentary example**: an integrated platform team might propose targeting hierarchical nanocomposite synthetic wood, starting with bioreactors to produce custom-designed cellulose-binding proteins and lignin polymerizing enzymes, that are input "inks" for a high-resolution, multi-channel deposition system with lignin and cellulose inks into a custom-built "directed self-assembly reactor" with initial bulk alignment anisotropy, in which pH, ionic concentration, temperature, and pressure are applied in 2-phases. First to template catalysis and wet-assembly, then to program dehydration. Finished by a microwave curing unit. In-line metrology might include x-ray or ultrasonic. The target metrics to be a foundational material that would displace current "synthetic wood" composites and natural woods might be: (1) Specific tensile strength of > 220 kN·m/kg; (2) < 2% water absorption by weight after 24-hour (per ASTM D570); (3) Ability to transition from a rigid zone (>10 GPa modulus) to a flexible zone (<2 GPa modulus) over a programmable transition length of less than 10 cm within a single, monolithic component; and (4) Production rate of > 0.01 m^3/hour.
+ While this example illustrates one possible process, we strongly encourage proposals that envision radically different platforms. We welcome living, non-living, organic, inorganic, and radically hybrid approaches. We have no bias for or against wood,

nor any of the other 5 provided examples. Teams should propose foundational material targets and platforms they feel intrinsically motivated to pursue, including why. Detailed selection criteria can be found in **Appendix 1**.

+ We expect ***specialists*** to propose their approach to 1-2 specific TAs.
+ We expect *ecosystem* ***contributors*** to propose a specific expertise that would be valuable across a wide range of *integrated platform* and *specialist* teams.

Phase 1 — Does the core assembly mechanism work? (18 months)

+ *Integrated Platform*:
    + Physical Goal: Demonstrate the core assembly mechanism at laboratory scale. This requires successfully synthesizing all required functionalised assembly precursors and proving the proposed assembly mechanism works on a small sample (*e.g.,* millimeter-scale). In this phase although structure and function must be characterised, there is no functional performance expectation.
    + Digital Goal: Develop and validate a rudimentary 'digital twin' with simulations that can predict a primary material property with at least moderate accuracy (*e.g.,* <50% error) when compared to an experimentally characterized result. The goal is to set up initial software infrastructure and develop a very crude compass to give some direction to initial physical experiments.
+ Synthetic wood example: a team should produce custom cellulose-binding and lignin-polymerizing proteins, and purchase/purify other biomass inputs. With a most likely manual procedure, produce a millimeter-scale, fully cured hierarchical composite. They should also demonstrate a digital twin that can predict the tensile strength of a simulated cellulose-lignin composite with some directional accuracy.
+ *Specialists* example goals:
    + Demonstrate a scalable exosome capture, functionalisation and stabilisation method for an existing bioprocess
    + After consultation with a platform team for specification, build a prototype programmable metasurface for directed alignment of assembly precursors.
+ *Ecosystem Contributor* example goals:
    + Analytical lab workflow established, with an array of standardised procedures for analytical characterisation of each final material class under development
    + A centralised digital infrastructure framework has been set up, with sufficient flexibility of data structures to incorporate the platform teams' and analytical laboratories needs. Consultation structure with teams set up, with responsible

    people and meeting formats established. Complete physical and digital tracking of processes, samples, and data under development.
    + Assisted multiple platform teams with prototype custom hardware and related control / data historian software for individual lab procedures or unit ops.
+ Go/No-Go Decision:
    + *integrated platform* teams that validate both their digital model and their core physical assembly principle will be eligible to apply for Phase 2 funding.
    + *Specialist* teams that wish to receive Phase 2 funding must either (a) join an existing *integrated platform* team, or (b) nucleate a new team around their now 18-month derisked core technology.
    + *Ecosystem* teams: contingent on the needs of *integrated platform* teams.

Phase 2 — Does the platform work? (24 months)

+ Integrated Platform:
    + Physical Goal: the first integrated, benchtop-scale prototype of the physical platform is built and operational. It must be able to produce a material sample of a meaningful size (*e.g.,* a 10x10 cm sheet).
    + Digital Goal: must demonstrate inverse design. The team must be able to input a target performance metric (e.g., 50% of the final goal) and have the model generate a viable 'recipe'. The digital twin's predictive accuracy must improve significantly (*e.g.,* <20% error).
    + Performance Goal: The prototype platform must be able to produce materials that are tunable across all of the final key performance metrics. This might look like generating a small library of material outputs. This proves the approach is on the right trajectory.
+ Synthetic wood example: The software platform should be able to target 3 material with varying <specific tensile strengths, water absorptions, and external geometries>, generate viable recipes to target each, then a benchtop prototype of the multi-ink deposition head and the two-phase assembly reactor will produce them within ~20% error. Some steps will probably still be manual.
+ *Ecosystem Contributor* example goals:
    + Standardised analytical characterisation of process intermediates and final materials is done routinely with minimal overhead.
    + Platform teams increasingly rely on the centralised data structures for their process design, including for data-driven ML/AI or hybrid methods.
+ Go/No-Go Point: If at least one *Integrated Platform* makes it this far, this programme will have a Phase 3, in which successful teams will be eligible for follow-on funding.

Phase 3 – Discover the process, scale a bit, change the world. (18 months)

To shoot towards the ultimate 5 year goal, ARIA will fund across teams in this phase a minimum additional ~£10 M as well as potentially significantly more co-raised funds from private/philanthropic capital. We expect the programme's learnings from Phases 1-2 to heavily influence what Phase 3 looks like. Some things we think are important to derisk in this phase include:

+ Scaling the process discovery efforts, production throughput, length-scale-up.
+ Probing and improving process robustness (to perturbations in inputs)
+ Exploring parallelisability, in particular for length-scale-up
+ Further increasing the accuracy of in-silico design systems to fully graduate from a directional compass to a precise programmer.
+ Productisability: Interfacing of output materials with existing mechanical, electrical or optical engineered systems.
+ Probing the "universal fabricator" claim by exploring the generality of the platform to discover processes that produce diverse functional outputs.

Existing creators may need to hire new specialists to tackle these new sets of challenges.

Questions we still have on translation & impact

+ What is the best way to facilitate / catalyse the formation (or hiring) of highly integrated, interdisciplinary teams? To be successful, does this programme require scientists and engineers of *integrated platform* teams to work together in the same physical space?
+ Our vision is very strongly scale-out; is this vision viable or should we be open to also considering more traditional scale-up? How much should we focus on scaling, is it an ARIA-shaped problem or should we hand it over to private capital once initial process discovery is done?
+ We have presented a strong list of constraints for specific applications for teams to target and 6 examples. Should we narrow it down even further? In particular are there specific target foundational materials that would be highly strategic for industry to be built specifically in the UK? Perhaps leveraging core competencies such as:
    - World-leading marine/ocean engineering expertise?
    - Highest *density* of creative talent in the world?
+ Is it realistic to establish a shared open data ecosystem for material process - structure - properties? Would having to share such valuable data discourage potential creators to apply and collaborate as part of the programme?

- Below are our beliefs underlying our IP vision. We would love challenges to it:
    - There are abundant, extremely high value materials that can be discovered on the platforms our programme aims to develop.
    - In recent history attempts at commercialising a material directly have failed, and thus the standard commercialisation strategy is the sell/license the process discovery platform or the final product (uniquely enabled by integrating the produced new material).
    - However, if the platform (including the data generated) is patented, the loss to society is large, because (1) the rate of material discovery will be stifled and (2) improvements to the platform will be stifled. Therefore, we think the **v1** platform and the generated data should be open.
    - Strong patents around a material and/or product will let a company scale it. Thus, if the foundational material is patented, the loss to society is less than the loss if the foundational material was not patented.
    - We believe that the platform will require specialisation to go from a process discovery tool to a foundational material process optimisation tool & scalable manufacturing platform. All of this can be patented around the specific material, without patenting the base **v1** platform.
- From those beliefs, below is our vision for IP sharing. We would love feedback on it:
    - During Phases 1-2, the process discovery software-hardware platform and all associated intellectual property rights must be made publicly available without encumbrance within 5 years of receiving the funding. We expect all creators to provide immediate non-exclusive licenses to other creators of all intellectual property related to the discovery software and hardware platform developed.
    - However, compositions and process recipes for particularly commercialisable materials may be patented by the grantee organisation, in particular, **all advances made during Phase 3 of the programme are patentable.**
    - All process and material data gained is to be shared as part of a standardised open dataset at the end of the programme (although particular discoveries may be patented for commercialisation before publication).
    - All analytical method procedures related to intermediate materials and final materials must be published within 5 years of receiving the funding, and reproducibility of the published procedures demonstrated with non-grantee laboratories.

APPENDIX

Appendix 1: What materials are in scope, in more detail

[Discover the in scope materials.]

Appendix 2: Out of scope

Some things that may be in scope for future funding calls in the *Manufacturing Abundance* Opportunity Space, but are NOT in scope for this programme:

+ Material targets that are not hierarchical nanocomposites that have the potential to be future foundational materials *e.g.,* therapeutics, specialty chemicals and/or other high-value nanomaterials
+ Funding materials discovery alone, without the development of a data-generating, hardware-software integrated platform for process discovery.
+ Sustainable/circular inputs: universal deconstructor (waste upcycling), scaling sustainable inputs
+ Democratising materials characterisation
+ Community building towards scale-out manufacturing abundance

Appendix 3: Technical Areas further reading

TA1.1 Further reading:

+ **Recent Progress in the Science of Complex Coacervation**, 2020 Sing, Charles E., and Sarah L. Perry. *Soft Matter* 16 (12): 2885–2914. https://doi.org/10.1039/D0SM00001A
+ **Three-Dimensional DNA-Programmable Nanoparticle Superlattices**, 2020 Kahn, Jason S, Brian Minevich, and Oleg Gang. *Current Opinion in Biotechnology* 63 (June): 142–50. https://doi.org/10.1016/j.copbio.2019.12.025
+ **From Vesicles to Materials: Bioinspired Strategies for Fabricating Hierarchically Structured Soft Matter**, 2021 Amstad, Esther, and Matthew J. Harrington. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379 (2206): 20200338. https://doi.org/10.1098/rsta.2020.0338
+ **Process Principles for Large-Scale Nanomanufacturing**, 2017 Behrens, Sven H., Victor Breedveld, Maritza Mujica, and Michael A. Filler. *Annual Review of Chemical and Biomolecular Engineering* 8 (1): 201–26. https://doi.org/10.1146/annurev-chembioeng-060816-101522
+ **Protein-Based Biological Materials: Molecular Design and Artificial Production**, 2023 Miserez, Ali, Jing Yu, and Pezhman Mohammadi. *Chemical Reviews* 123 (5): 2049–2111. https://doi.org/10.1021/acs.chemrev.2c00621

TA.1.2 Further reading:

+ **Acoustically Shaped DNA-Programmable Materials**, 2024 Arnon, Z. A., S. Piperno, D. C. Redeker, E. Randall, A. V. Tkachenko, H. Shpaisman, and O. Gang. *Nature Communications* 15 (1): 6875. https://doi.org/10.1038/s41467-024-51049-7

+ **Production of Synthetic Spider Silk Fibers**, 2016 Copeland, Cameron G. 4879. All Graduate Theses and Dissertations. https://digitalcommons.usu.edu/etd/4879
+ **Flow-Induced Crystallisation of Polymers from Aqueous Solution**, 2020 Dunderdale, Gary J., Sarah J. Davidson, Anthony J. Ryan, and Oleksandr O. Mykhaylyk. *Nature Communications* 11 (1): 3372. https://doi.org/10.1038/s41467-020-17167-8
+ **3D Printing Hierarchical Porous Nanofibrous Scaffold for Bone Regeneration**, 2025 Hu, Zhiai, Hengyi Lin, Zhenming Wang, Yating Yi, Shujuan Zou, Hao Liu, Xianglong Han, and Xin Rong. *Small (Weinheim an Der Bergstrasse, Germany)* 21 (2): e2405406. https://doi.org/10.1002/smll.202405406
+ **Scalable Production of Structurally Colored Composite Films by Shearing Supramolecular Composites of Polymers and Colloids**, 2024 Li, Miaomiao, Bolun Peng, Quanqian Lyu, Xiaodong Chen, Zhen Hu, Xiujuan Zhang, Bijin Xiong, Lianbin Zhang, and Jintao Zhu. *Nature Communications* 15 (1): 1874. https://doi.org/10.1038/s41467-024-46237-4
+ **Electrically Programmable Solid-State Metasurfaces via Flash Localised Heating**, 2023 Zangeneh Kamali, Khosro, Lei Xu, Nikita Gagrani, Hark Hoe Tan, Chennupati Jagadish, Andrey Miroshnichenko, Dragomir Neshev, and Mohsen Rahmani. *Light: Science & Applications* 12 (1): 40. https://doi.org/10.1038/s41377-023-01078-6

TA1.3 Further reading:

+ **The FAIR Guiding Principles for Scientific Data Management and Stewardship**, 2016 Wilkinson, Mark D., Michel Dumontier, IJsbrand Jan Aalbersberg, Gabrielle Appleton, Myles Axton, Arie Baak, Niklas Blomberg, et al. *Scientific Data* 3 (1): 160018. https://doi.org/10.1038/sdata.2016.18
+ **Toward a Unified Description of Battery Data**, 2022 Clark, Simon, Francesca L. Bleken, Simon Stier, Eibar Flores, Casper Welzel Andersen, Marek Marcinek, Anna Szczesna-Chrzan, et al. *Advanced Energy Materials* 12 (17): 2102702. https://doi.org/10.1002/aenm.202102702
+ **Machine Learning for Analyses and Automation of Structural Characterization of Polymer Materials**, 2024 Lu, Shizhao, and Arthi Jayaraman. *Progress in Polymer Science* 153 (June): 101828. https://doi.org/10.1016/j.progpolymsci.2024.101828
+ **Multi-Hierarchical Profiling the Structure-Activity Relationships of Engineered Nanomaterials at Nano-Bio Interfaces | Nature Communications**, 2018 Multi-Hierarchical Profiling the Structure-Activity Relationships of Engineered Nanomaterials at Nano-Bio Interfaces | Nature Communications. https://www.nature.com/articles/s41467-018-06869-9
+ **Nanoindentation Studies of the Mechanical Behaviours of Spark Plasma Sintered Multiwall Carbon Nanotubes Reinforced Ti6Al4V Nanocomposites**, 2019 Okoro, Avwerosuoghene Moses, Ronald Machaka, Senzeni Sipho Lephuthing, Samuel Ranti Oke, Mary Ajimegoh Awotunde, and Peter Apata Olubambi. *Materials Science and Engineering: A* 765 (September): 138320. https://doi.org/10.1016/j.msea.2019.138320

TA1.4 Further reading:

+ **Machine Learning for Molecular and Materials Science**, 2018 Butler, Keith T., Daniel W. Davies, Hugh Cartwright, Olexandr Isayev, and Aron Walsh. *Nature* 559 (7715): 547–55. https://doi.org/10.1038/s41586-018-0337-2
+ **Hierarchically Structured Nanocomposites via a 'Systems Materials Science' Approach**, 2022 Li, Rebecca L., Carl J. Thrasher, Theodore Hueckel, and Robert J. Macfarlane. *Accounts of Materials Research* 3 (12): 1248–59. https://doi.org/10.1021/accountsmr.2c00153
+ **Active Learning in Materials Science with Emphasis on Adaptive Sampling Using Uncertainties for Targeted Design**, 2019 Lookman, Turab, Prasanna V. Balachandran, Dezhen Xue, and Ruihao Yuan. *Npj Computational Materials* 5 (1): 21. https://doi.org/10.1038/s41524-019-0153-8
+ **Hierarchically Structured Bioinspired Nanocomposites**, 2023 Nepal, Dhriti, Saewon Kang, Katarina M. Adstedt, Krishan Kanhaiya, Michael R. Bockstaller, L. Catherine Brinson, Markus J. Buehler, et al. *Nature Materials* 22 (1): 18–35. https://doi.org/10.1038/s41563-022-01384-1
+ **Modelling and Analysis of Multiscale Hybrid Composite Structures for Virtual Design and Performance-Driven Manufacturing: A Review**, 2025 Patadia, Mitesh, and Rebekah Sweat. *Advances in Materials and Processing Technologies*, April. https://www.tandfonline.com/doi/abs/10.1080/2374068X.2024.2373570
+ **Understanding and Modeling Polymers: The Challenge of Multiple Scales**, 2023 Schmid, Friederike. *ACS Polymers Au* 3 (1): 28–58. https://doi.org/10.1021/acspolymersau.2c00049
+ **Multiscale Modeling and Simulation of Polymer Nanocomposites**, 2008 Zeng, Q.H., A.B. Yu, and G.Q. Lu. *Progress in Polymer Science* 33 (2): 191–269. https://doi.org/10.1016/j.progpolymsci.2007.09.002

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