Crystal Palace

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Making inorganic materials that we cannot make today

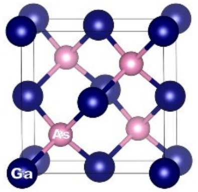
Proposers Day

December 5, 2025

DARPA

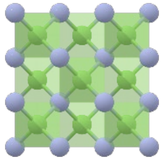
DoW systems demand new inorganic material innovations

Past: revolutionary capabilities made possible by materials



GaAs

https://en.wikipedia.org/wiki/Precision_Lightweight_GPS_Receiver



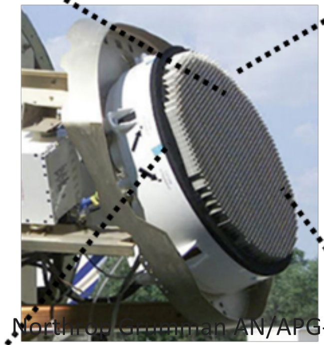
GaN

https://en.wikipedia.org/wiki/AN/SPY-6

Present: many desired materials still under development

Magnetics
Wide bandwidth communications

Piezoelectrics
In-band EW protection

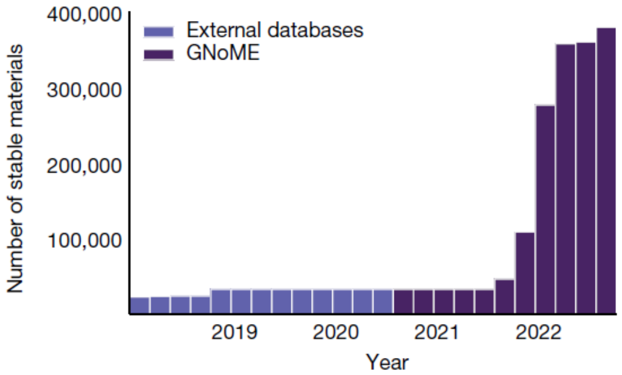


Northrop Grumman AN/APG-81

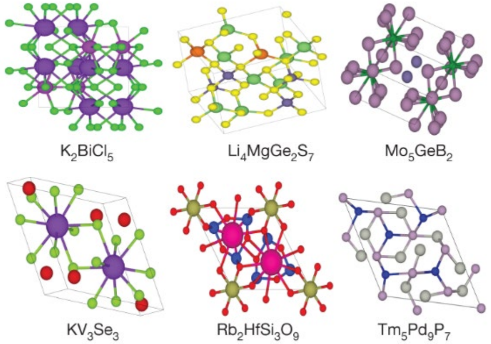
Semiconductors
High power and range

Dielectrics
Low leakage passives

Future: explosion of complex material design



Google, Nature 2023



Google, Nature 2023

More elements, more structures = enlarged material property space

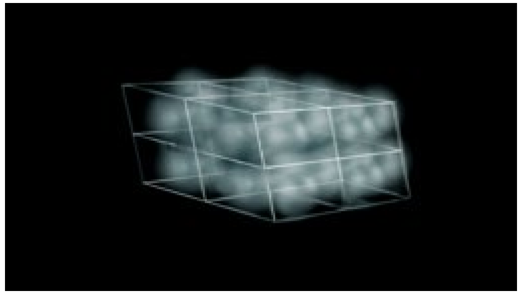
The bottleneck is the realization of high-quality complex materials at scale

PLGR: precision lightweight GPS receiver; AESA: active electronically scanned array **DISTRIBUTION STATEMENT A.** Approved for public release: distribution unlimited.

New tools and techniques for new complex inorganic materials

Crystal Palace

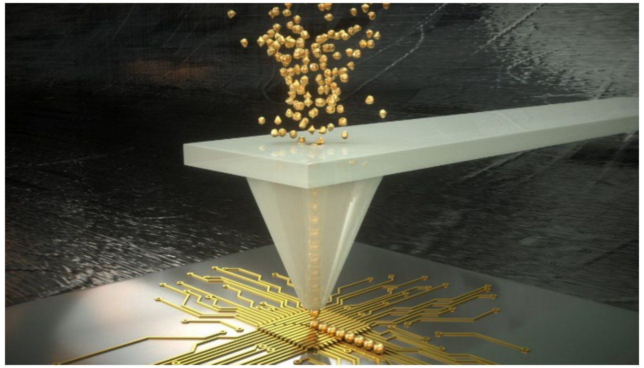
Design



New complex inorganic materials

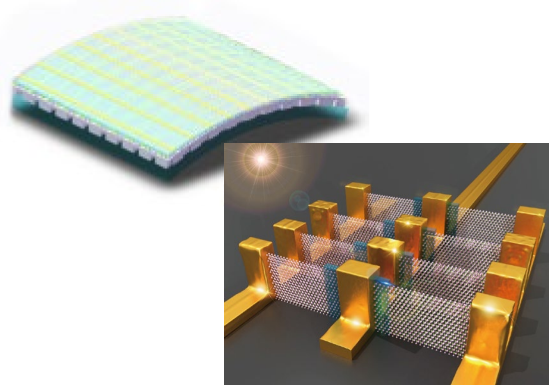
Make

Generalizable process



Relevant scale

Integrate



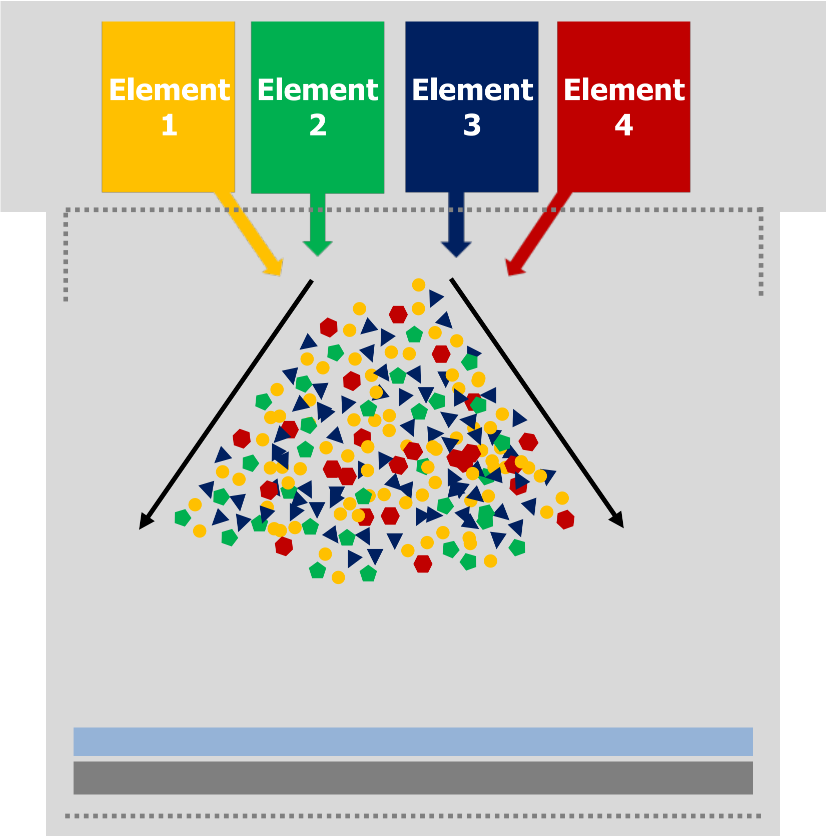
Devices in microsystems

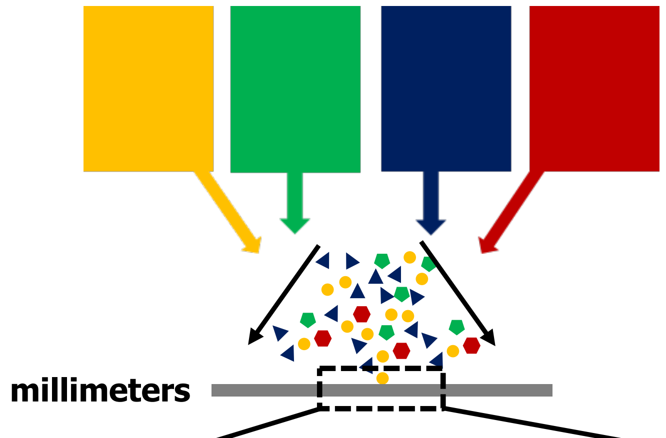
Peplow, *Nature* 2025
Liu et al., *Nano-Micro Lett.* 2024
https://pme.uchicago.edu/new-projects/mbe-system-direct-printing-quantum-circuits
https://www.leti-cea.com/cea-tech/leti/english/Pages/What-s-On/Integration-of-2D-materials-in-VLSI-electronic-devices.aspx

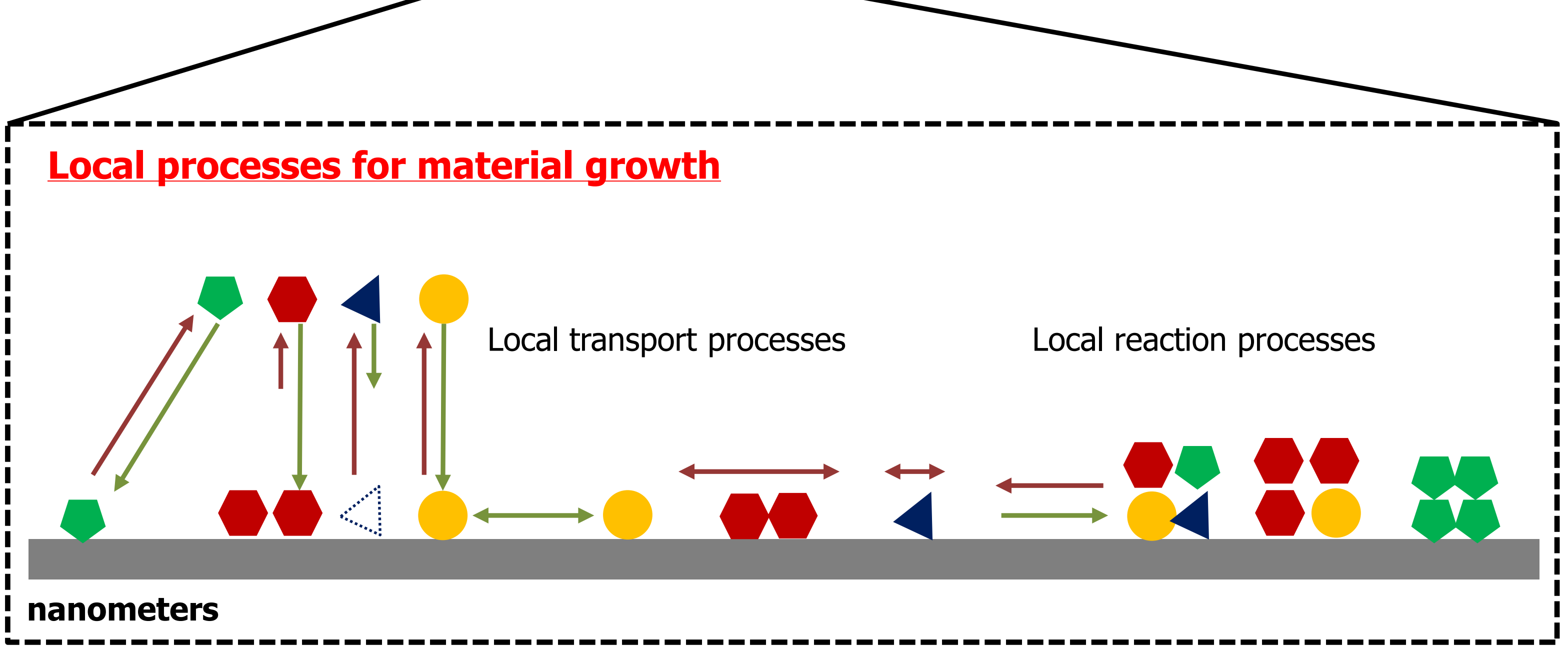
Crystal Palace will enable the rapid development of new, complex, inorganic materials at scale

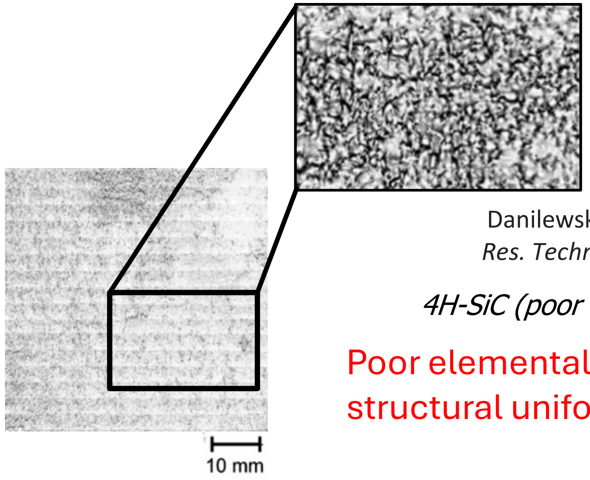
Global controls are used for local processes

Global controls:
- **Temperature**
- **Pressure**
- **Elemental flux**









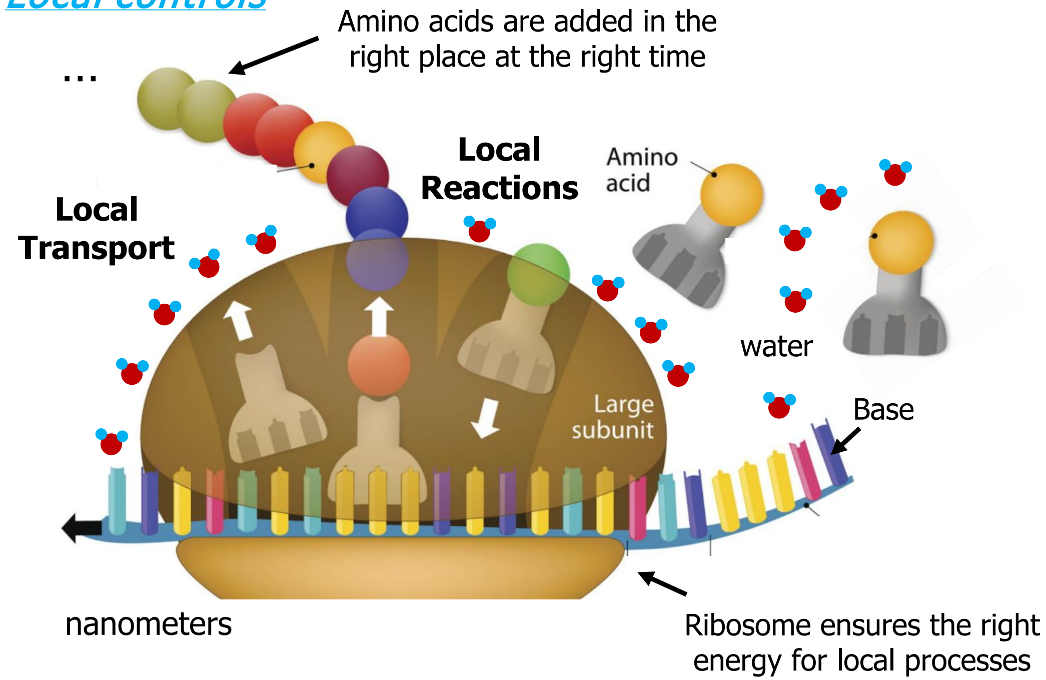
Danilewsky, *Cryst. Res. Technol.* 2020

4H-SiC (poor quality)

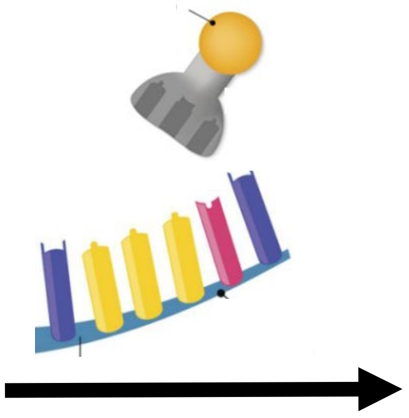
Poor elemental and structural uniformity

Biology uses local controls for local processes

Local controls

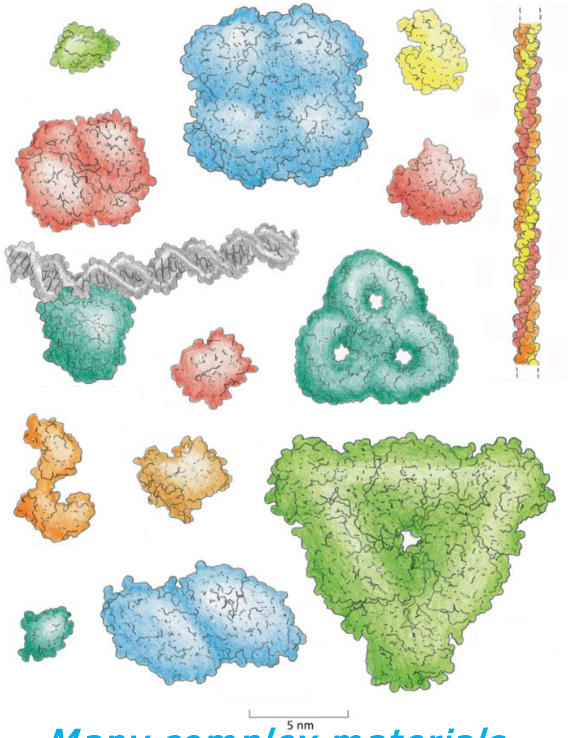


Ribosome



Generalizable

Adapting the order of bases enables rapid changes in composition and structure



Many complex materials

Essential Cell Biology 5th Edition, 2019

Local controls offer a new path for complex inorganic materials

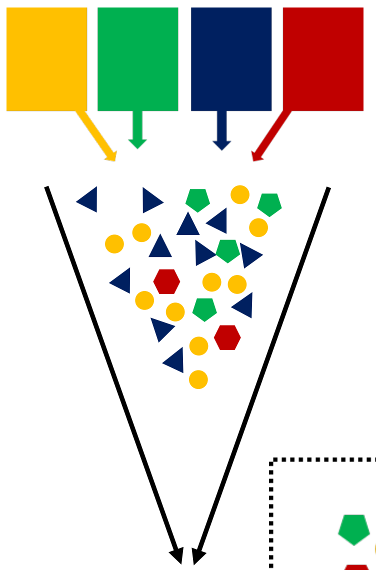
Crystal Palace will create a new class of tools and techniques with controls that are local and generalizable

Technical Challenge 1:
Precise local control of transport and reaction processes

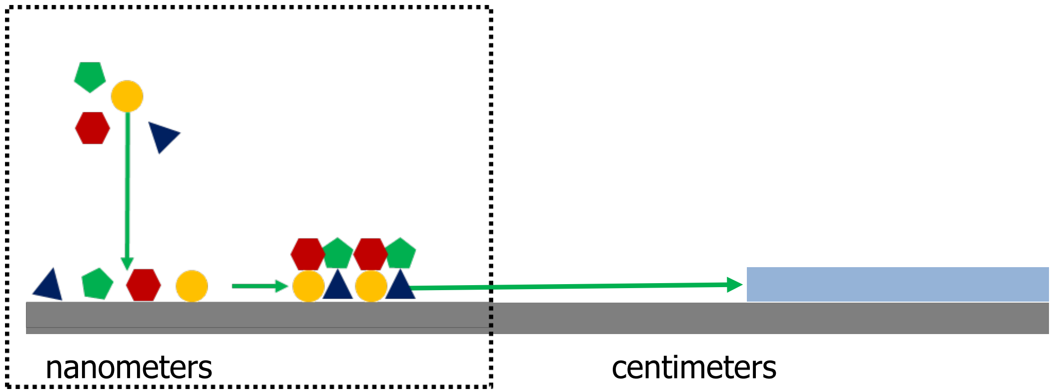
How to make it uniformly

Technical Challenge 2:
Generalized control for many complex materials

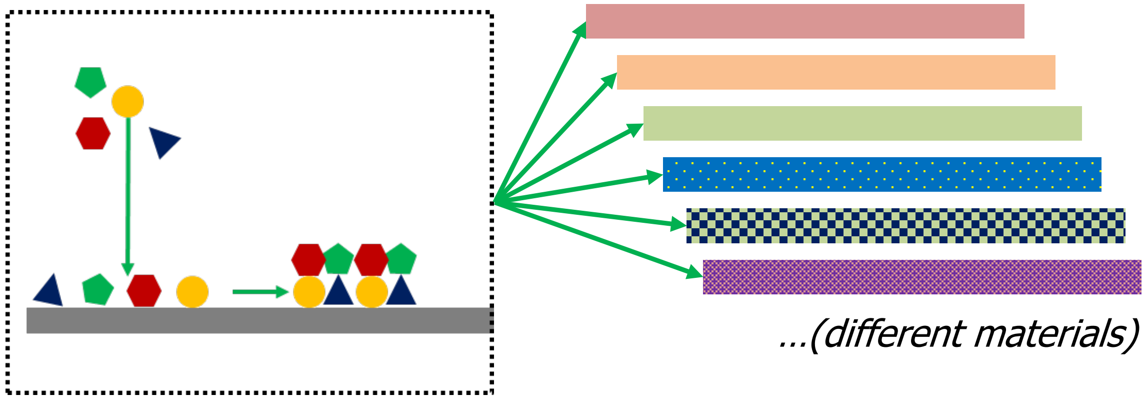
How to make many materials



Local control



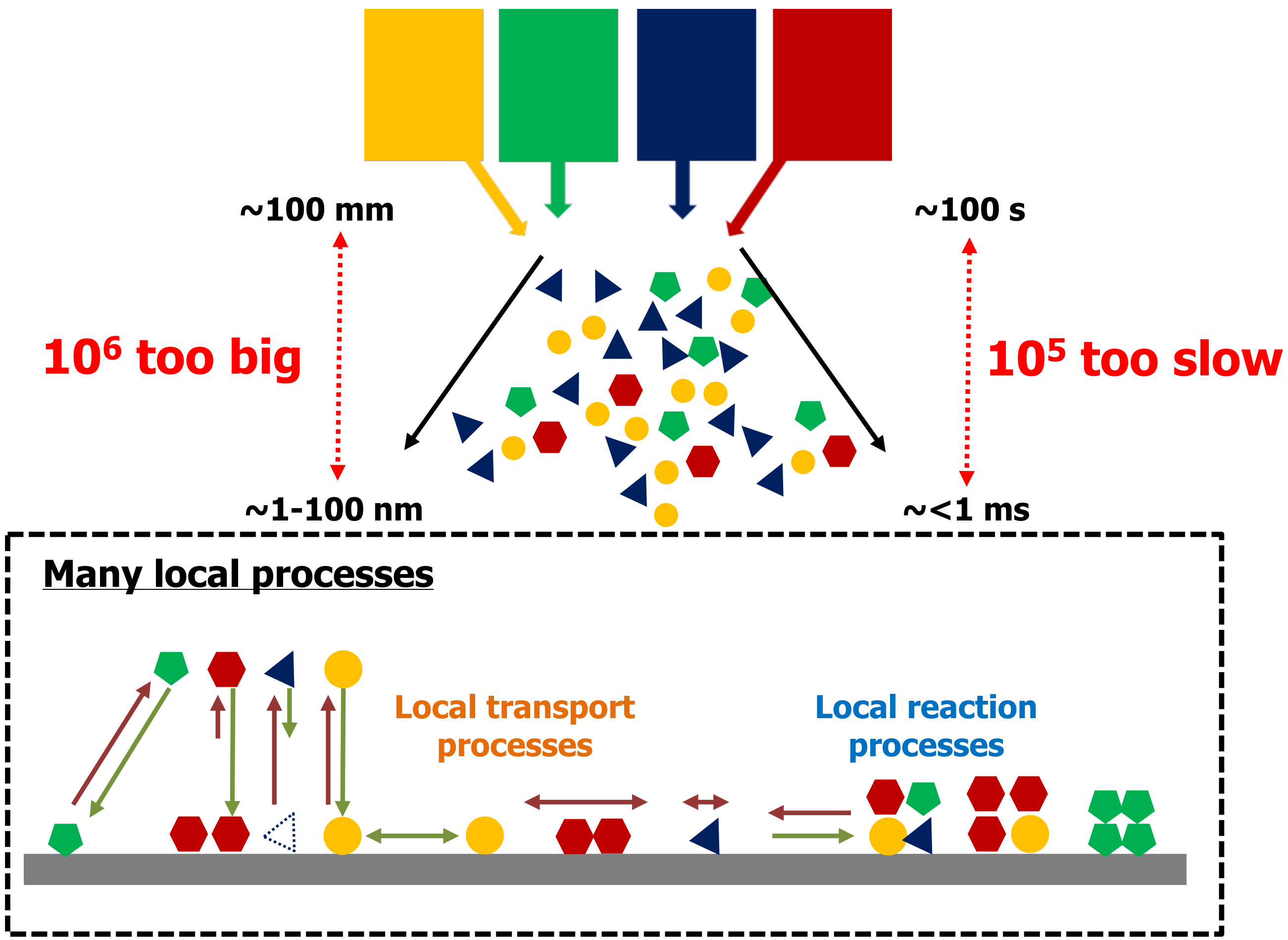
Generalizable



Crystal Palace will demonstrate rapid development of many new complex materials

TC1: Precise local control of transport and reaction processes

Today's controls are too big and too slow



Today's tools have too few controls

Local transport: right place, right time

1) Rate of adsorption

$$R_{ads,1} \propto pressure \times (1-\theta_1) \times {}^{E_{a,1}}/_{RT}$$

2) Rate of desorption

$$R_{des,1} \propto \theta_1 \times {}^{E_{b,1}}/_{RT}$$

…for each element

3) Surface diffusion flux

$$J_1 \propto D_1 \times C_1$$

Local reactions: right structure across scale

4) Rate of stable structure formation

…for each structure

$$I \propto (1-\theta_1) \times jump\ frequency \times {}^{E_{c,1}}/_{RT}$$

5) Rate of growth

$$U \propto jump\ distance \times jump\ frequency \times {}^{E_{d,1}}/_{RT}$$

Others: gas phase processes, collisions, etc.

Too big, too slow, and too few controls lead to undesirable material growth

TC2: Generalizable controls for many complex materials

Different materials require different local parameters

Some controls work well on some local processes, but not on others

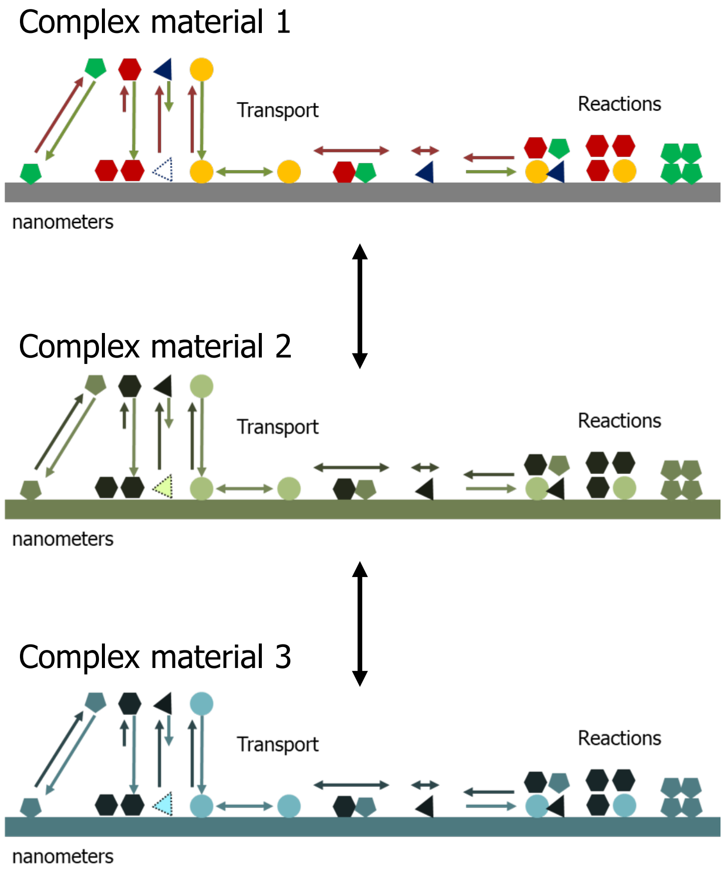
Example:

Light controllable reaction

$$Fe(CO)_5 \rightarrow Fe + 5CO$$

Not light controllable reaction

$$TiCl_4 \rightarrow Ti + Cl_4$$



n equations

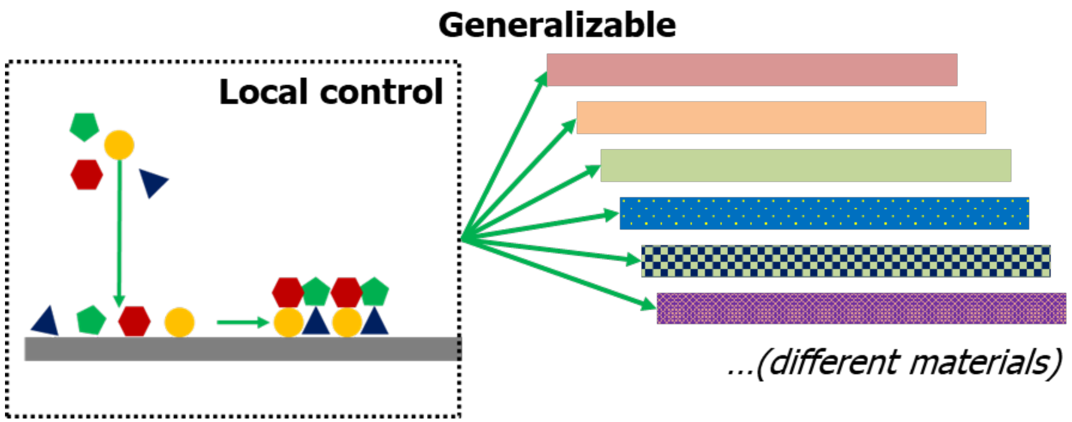
n *different* equations

n *different* equations

Need controls that can be adapted to grow a broad range of materials

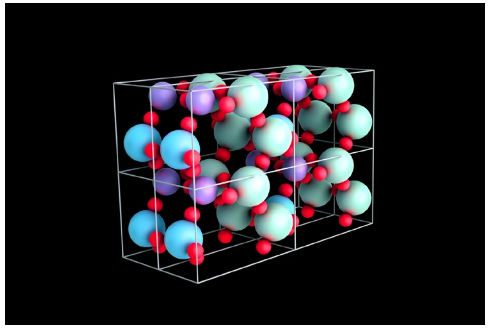
Crystal Palace will create new tools and techniques for complex inorganic materials

Technical Challenge 1:
Precise local control of transport and reaction processes

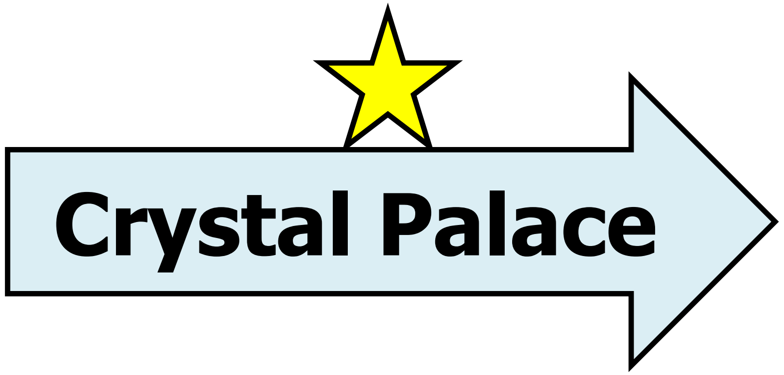


Technical Challenge 2:
Generalized control for many complex materials

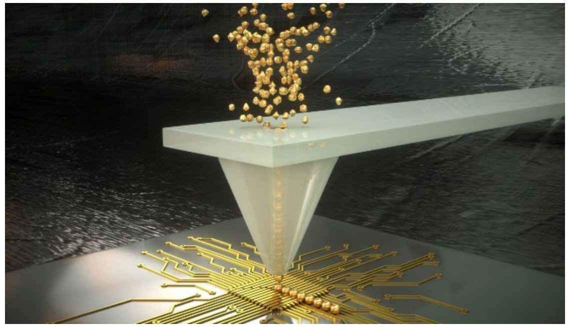
Design



Peplow, *Nature* 2025



Make



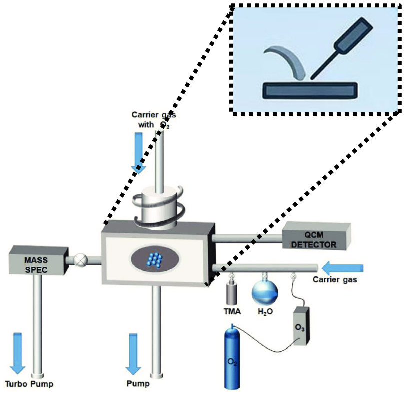
https://pme.uchicago.edu/new-projects/mbe-system-direct-printing-quantum-circuits

Crystal Palace will bridge the gap between design and making of complex materials

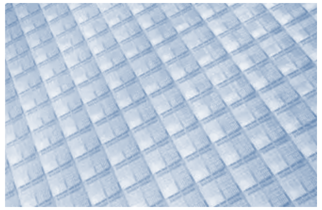
Program structure: OT-based agreements

Phase 1 (18 months)

Wang et al., *Adv. Mater. Interfaces* 2018



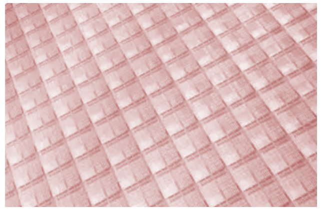
Usable growth technique with local control



Recipe for CM 1 at demonstration scale*

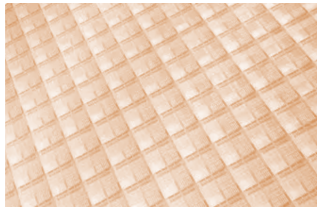
Recipe for CM 2, CM 3, and CM 4 at sample-scale**

Phase 2.1 (6 months)



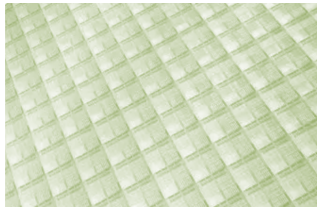
Recipe for CM 2 at demonstration scale*

Phase 2.2 (6 months)



Recipe for CM 3 at demonstration scale*

Phase 2.3 (6 months)



Recipe for CM 4 at demonstration scale*

	Phase 1	Phase 2.1	Phase 2.2	Phase 2.3
Objective:	*Prove feasibility*	*Increase complexity*	*Prove generalizability*	*Establish transferable process*

*Demonstration scale is 2 inches
**Sample scale is 1 cm minimum to characterize structure

CM: complex material

Material constraints table

New complex material (CM) [1]		CM 1 (Phase 1)	CM 2 (Phase 2.1)	CM 3 (Phase 2.2)	CM 4 (Phase 2.3)
Material complexity [2]	Elemental complexity	≥ 2 elements	≥ 3 elements	≥ 3 elements	≥ 4 elements
	Structural complexity	≥ 4 possible crystal structures	≥ 5 possible crystal structures	≥ 6 possible crystal structures	≥ 6 possible crystal structures
Material type (property) [3]		Examples: Semiconductors, magnetics, piezoelectrics, dielectrics, ferroelectrics, or superconductors			
Material class (chemistry) [3]		Examples: Oxides, nitrides, chalcogenides, or mixed metals			
Material thickness [4]		≥ 20 nm			≥ 20 nm and ~ 0.5 µm [5]
Growth rate		≥ 0.1 nm/min			

1. Proposer-defined CM that has **not been previously grown as a single crystal on a ≥ 2-inch scale, has a clear target application, and is stable at room temperature**. Desired material composition and crystal structure must be pre-defined.
2. Either elemental **OR** structural complexity constraints must be met.
3. Performers must select at least two different material types and classes. Proposers may propose other material types or classes with justification.
4. Unless the desired material property can only be exhibited outside of this thickness range; in which case, performers must provide justification.
5. At the end of Phase 2, at least one CM must be demonstrated at both the thin (~ 20 nm) and thick (~ 0.5 µm) limit.

CM: complex material

Program metrics

Metrics	Phase 1 (18 months)		Phase 2.1 (6 months)	Phase 2.2 (6 months)	Phase 2.3 (6 months)
Complex materials (CM)	CM 1 at ≥ 2″ scale	CM 2,3,4 at sample-scale [1]	CM 2 at ≥ 2″ scale	CM 3 at ≥ 2″ scale	CM 4 at ≥ 2″ scale
Single crystal quality [2,3]	≤ 0.3°	≤ 1°	≤ 0.3°	≤ 0.3°	≤ 0.3°
Material non-uniformity [4]	± 5%	N/A	± 5%	± 5%	± 5%
Process reproducibility [5]	≥ 3	N/A	≥ 3	≥ 3	≥ 3
Material property	Proposer-defined properties [5]				

1. The CM sample-scale is 1 cm minimum to characterize crystal structure. Sample-scale CM must be demonstrated at ≥ 2-inch scale in succeeding program phases.
2. Full width at half maximum (FWHM) of a specific X-ray diffraction (XRD) peak over a sampling point.
3. Cross-sectional transmission electron microscopy (TEM) is required to validate that the desired single crystalline structure was achieved for each CM.
4. Non-uniformity of the measured XRD peak FWHM using at least nine evenly distributed points across the sample (ratio of standard deviation to mean).
5. Number of repeated growth runs on 2-inch scale samples meeting single crystal quality and material non-uniformity metrics.
6. Based on the proposed material types at each phase, measured key material property (e.g., carrier mobility, optical bandgap, magnetic permeability, or piezoelectric coefficient) is required.

CM: complex material

Transition strategy

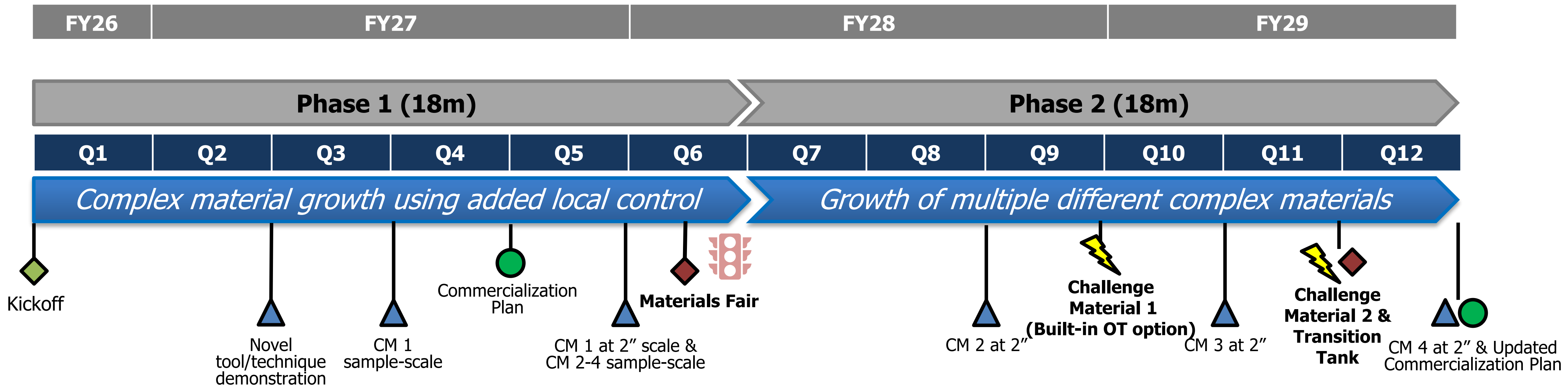
Commercialization/transition outline:

1. Commercialization plan required in the PA and must be submitted as part of proposal
2. Detailed commercialization plan delivered by performers by end of Phase 1
3. Materials Fair
4. Transition Tank
5. Finalized commercialization plan that includes any outputs from the Materials Fair and Transition Tank

Example commercialization plans:

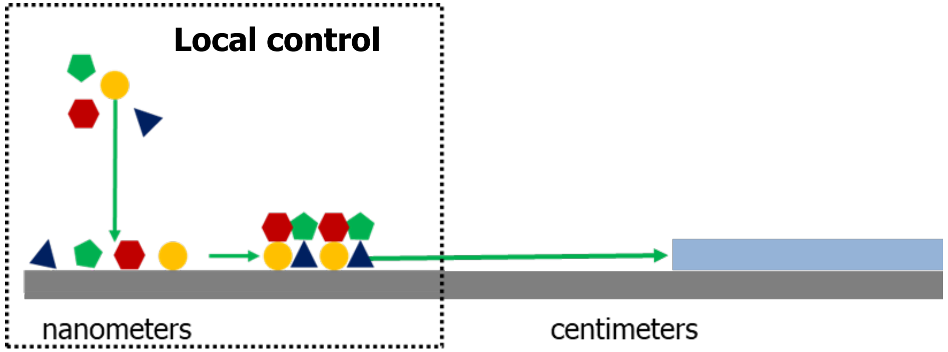
small business or spin-off company, licensing to large deposition tool companies, or materials as a service

Program structure and schedule



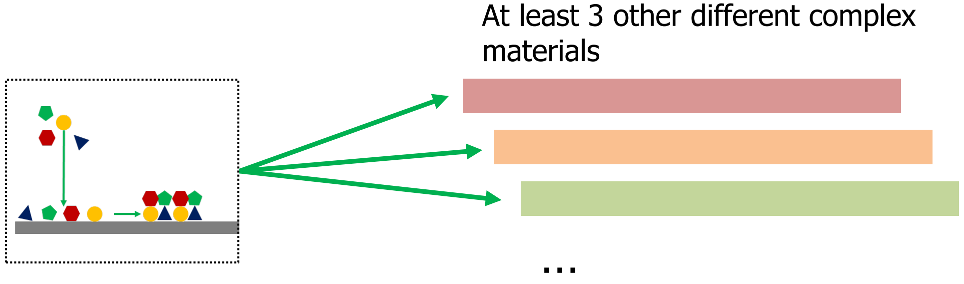
Program objectives:

Phase 1: Prove the feasibility of controlling composition, structure, and single crystal uniformity of a complex material



Phase 2: Prove the generalizability of controlled growth technique to rapidly synthesize multiple complex materials

Generalizable growth approach



CM: complex material

www.darpa.mil