

## Nanoparticles exploring the macroscopic world

**Citation for published version (APA):**

van Ravensteijn, B. G. P., & Voets, I. K. (2021). Nanoparticles exploring the macroscopic world. *Matter*, 4(8), 2661-2663. <https://doi.org/10.1016/j.matt.2021.06.047>

**Document license:**

TAVERNE

**DOI:**

[10.1016/j.matt.2021.06.047](https://doi.org/10.1016/j.matt.2021.06.047)

**Document status and date:**

Published: 04/08/2021

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

the end. Just as organoid technology is still in its infancy with constant developments, it is exciting to see what success others achieve from building on or adapting this approach, with a dream of clinical use for these lab-grown organs or even being able to research cell-cell interactions in a programmable context.

### ACKNOWLEDGMENTS

This work was financially supported by Institute of Bioengineering and Bioimaging, Agency for Science, Technology and Research, Singapore.

1. Kim, J., Koo, B.K., and Knoblich, J.A. (2020). Human organoids: model systems for human biology and medicine. *Nat. Rev. Mol. Cell Biol.* *21*, 571–584.
2. Laurent, J., Blin, G., Chatelain, F., Vanneaux, V., Fuchs, A., Larghero, J., and Théry, M. (2017). Convergence of microengineering and cellular self-organization towards functional tissue manufacturing. *Nat. Biomed. Eng.* *1*, 939–956.
3. Brassard, J.A., Nikolaev, M., Hübscher, T., Hofer, M., and Lutolf, M.P. (2021). Recapitulating macro-scale tissue self-organization through organoid bioprinting. *Nat. Mater.* *20*, 22–29.
4. Sato, T., van Es, J.H., Snippert, H.J., Stange, D.E., Vries, R.G., van den Born, M., Barker, N., Shroyer, N.F., van de Wetering, M., and Clevers, H. (2011). Paneth cells constitute the niche for Lgr5 stem cells in intestinal crypts. *Nature* *469*, 415–418.
5. Yokoi, Y., Nakamura, K., Yoneda, T., Kikuchi, M., Sugimoto, R., Shimizu, Y., and Ayabe, T. (2019). Paneth cell granule dynamics on secretory responses to bacterial stimuli in enteroids. *Sci. Rep.* *9*, 2710.
6. Sachs, N., Tsukamoto, Y., Kujala, P., Peters, P.J., and Clevers, H. (2017). Intestinal epithelial organoids fuse to form self-organizing tubes in floating collagen gels. *Development* *144*, 1107–1112.
7. Stzepourginski, I., Nigro, G., Jacob, J.M., Dulauroy, S., Sansonetti, P.J., Eberl, G., and Peduto, L. (2017). CD34+ mesenchymal cells are a major component of the intestinal stem cells niche at homeostasis and after injury. *Proc. Natl. Acad. Sci. USA* *114*, E506–E513.
8. Hofer, M., and Lutolf, M.P. (2021). Engineering organoids. *Nat. Rev. Mater.* *6*, 1–19.

## Nanoparticles exploring the macroscopic world

Bas G.P. van Ravensteijn<sup>1,2,\*</sup> and Ilja K. Voets<sup>1,\*</sup>

**Macroscopic material properties are ultimately determined by the microstructural arrangement of building blocks. Bottom-up material fabrication routes exploit this central dogma by reverse-engineering the required building blocks from a targeted structure or property. Despite the plethora of available building blocks, bridging the gap between the microscopic and macroscopic world remains a formidable task. Recently, Macfarlane and co-workers approached this challenge by developing sintering-inspired processing strategies for nanoparticles, allowing the production of centimeter-scale objects while maintaining order on a single-particle level.**

Using colloidal particles as elementary building blocks for the bottom-up fabrication of designer materials is one of the pillars of modern day colloid and material science.<sup>1,2</sup> Their dimensions (10–1,000 nm) render them uniquely suited for this purpose because the particles are sufficiently small for autonomous recruitment and assembly via Brownian motion yielding superstructures with unique photonic, phononic, and mechanical properties. Analogous to atomic and molecular materials, the building block arrangements in the

assembled state determine the material properties. The internal structure of the self-assembled state is in turn dictated by the size and shape of the particles and the interactions acting between them.

Motivated by this, and sparked by significant advances in colloid synthesis, an impressive set of building blocks for self-assembly purposes was developed.<sup>3</sup> Where shape and size are mainly dictated by the bulk materials of the colloids and the selected particle

formation protocols, the interparticle interactions are readily tunable by decorating the surface of the particles with dedicated molecular entities.<sup>4</sup> Celebrated examples include colloidal particles functionalized with highly specific sticky DNA sequences,<sup>5</sup> metal coordination ligands,<sup>6</sup> or supramolecular host-guest binding motifs.<sup>7</sup> Perhaps surprisingly, this profound control over the individual particles does generally not propagate to macroscopic length scales. Reasons underlying this can be manifold and typically relate to limited availability of the building blocks, slow ordering, or the inclusion of ordering faults that limit further assembly.

To circumvent these drawbacks and take the first step toward fulfilling the

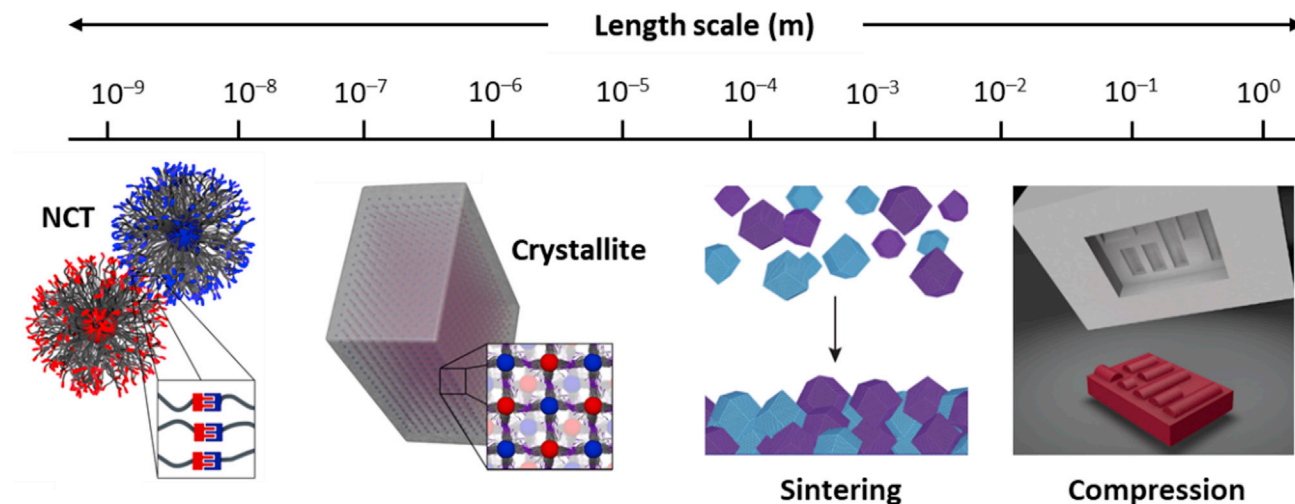
<sup>1</sup>Institute for Complex Molecular Systems, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, PO Box 513, Eindhoven 5600 MB, the Netherlands

<sup>2</sup>Present address: Department of Pharmaceutics, Utrecht Institute for Pharmaceutical Sciences (UIPS), Faculty of Science, Utrecht University, Universiteitsweg 99, Utrecht 3584 CG, the Netherlands

\*Correspondence:  
b.g.p.vanravensteijn@uu.nl (B.G.P.v.v.R.),  
i.voets@tue.nl (I.K.V.)

<https://doi.org/10.1016/j.matt.2021.06.047>





**Figure 1. Schematic overview of the processing route toward hierarchically structured macroscopic materials assembled from nanoparticle superlattices**

The elementary building blocks are nanocomposite tectons (NCTs). NCTs are inorganic nanoparticle cores decorated with end-functionalized polymer brushes. The terminal end groups (blue and red) can form inter-particle hydrogen bonds that drives the NCT assembly into micron-sized crystallites. These crystallites are subsequently converted into macroscopic materials via sintering and compression shaping. Sintering allows the crystallites to fuse together forming polycrystalline supercolloidal materials. By mild compression in a mold, these sintered materials can be deformed into any arbitrary shape. Throughout the fabrication process, the local NCT crystallinity is maintained, safeguarding compositional and structural control from the nano- to macroscopic scale (left to right).

promise of bottom-up creation of colloidal materials, the MacFarlane group developed a strategy to rapidly assemble gram-scale quantities of nanoparticles into macroscopic objects (Figure 1).<sup>8</sup> The building blocks of choice are so-called nanocomposite tectons (NCTs), which are inorganic nanoparticles (iron oxide) decorated with polymer brushes (polystyrene, PS). In this polymer brush, all the macromolecular chains are end-functionalized with supramolecular motifs that are able to form inter-particle hydrogen bonds.<sup>9</sup> Both the inorganic cores and polymers can be readily synthesized, making the NCTs unique in combining tunability and scalability. As shown in earlier work,<sup>9</sup> these NCTs readily assemble into faceted superlattice crystallites with dimensions ranging from 500 nm to several tens of micrometers. The obtained crystallites were subsequently used as higher-order building blocks for the fabrication of macroscopic objects. Inspiration was taken from well-known sintering protocols of nanocrystalline compacts of conventional metallic, ceramic, and

polymeric materials.<sup>10</sup> For these materials, application of high pressures and/or temperatures weakens the bonding interactions, enabling (powder) particles to plastically deform and form a densified continuous material. Considering that the forces holding the NCTs together are weaker than typical atomic or molecular interactions, analogous sintering procedures could be performed under mild conditions. Compression via centrifugation at room temperature for only 10 minutes proved to be sufficient to generate monolithic solids. In these solids, the different crystallites were firmly interconnected by newly formed hydrogen bonds between free-dangling supramolecular binding motifs at the crystallite's periphery. Given the high internal structural stability of the crystallites, the local particle ordering was not affected by this mild sintering. By following this material processing protocol, Macfarlane and co-workers basically decoupled the initial crystallization of NCTs and the use of the resulting crystallites as elementary building blocks in subsequent assembly

steps. This decoupling facilitates the bridging of multiple length scales in true hierarchical assembly pathways; a pivotal result in the (nano)particle assembly field.

An additional key feature of the formed solids is that they can be isolated as free-standing materials without disrupting their (local) order. This was achieved by gradually decreasing the solvent quality of the dispersing medium for the polymer chains that connect the hydrogen bonding moieties to the nanoparticle cores. Consequently, solvent is expelled, and the polymer brushes adopt a collapsed conformation. In the collapsed state, the fraction of solvent in the solid is negligible, thus facilitating their isolation in densified, free-standing solids by simply evaporating the solvent. Small-angle X-ray scattering (SAXS) and scanning electron microscopy (SEM) analysis confirmed that the materials remained intact and structurally ordered during drying. The final result is therefore a nanoparticle bulk material that is truly reminiscent to typical polycrystalline

bulk solids, where individual crystalline domains are connected via grain boundaries.

With the proof of concept in hand, the authors further highlighted the robustness of their approach by showing that the fabrication process also works with gold-based NCTs. Furthermore, monolithic solids with mixed compositions of iron oxide and gold were prepared. For these composites, the level of structural homogeneity could be controlled by the details of the fabrication route. Mixing both particle species directly from the start led to microscopically homogeneous materials, where the crystal unit cells contain the same number of gold and iron oxide particles. Alternatively, faceted supra-crystals consisting of solely gold or iron oxide particles could be made and subsequently processed into bulk solids by the previously mentioned sintering and drying strategy. Following this route, materials with heterogeneous microstructures were obtained as the gold and iron oxide domains remained phase separated during processing. Consequently, the ratio of gold to iron oxide and relative domain size could be controlled on microscale levels. This structural and compositional control was manifested by either strong or weak plasmon coupling between the gold particles depending on the average distance between them.

Finally, it was shown that these nano-based materials can be manipulated on even larger length scales. The sintered and isolated solids could be shaped into any arbitrary shape by

gently pressing them into a mold. Only weak compression forces were required, ensuring that the crystalline microstructure was not affected.

In summary, Macfarlane and co-workers showed in an impressive way that repurposing traditional processing routes for bulk materials for a robust and programmable colloidal system is a promising route to truly bridge the gap between the nanoscopic and macroscopic world. We anticipate that the ability to produce hierarchically ordered materials with tunable composition, nanoscale ordering, and microstructures has great implications for material science. Because the fabrication process is in principle generic and can be applied to any type of nanoparticle, materials with highly tunable plasmonic coupling, photoluminescence, or magnonic bandgaps are within reach. Besides the prospect of materials with new functions and properties, this work might lay the groundwork for further expanding our knowledge and understanding of traditional processing routes applied to atomic and molecular materials by *in situ* visualization of the elementary building blocks during, e.g., sintering or compression.

### ACKNOWLEDGMENTS

This work was performed using funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 838585 – STAR Polymers (B.G.P.v.R). I.K.V. acknowledges the Netherlands Organization for Scientific Research (NWO VIDI grant 723.014.006) for financial support.

### AUTHOR CONTRIBUTIONS

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

### DECLARATION OF INTERESTS

The authors declare no competing interests.

1. Boles, M.A., Engel, M., and Talapin, D.V. (2016). Self-Assembly of Colloidal Nanocrystals: From Intricate Structures to Functional Materials. *Chem. Rev.* 116, 11220–11289.
2. Vogel, N., Retsch, M., Fustin, C.A., Del Campo, A., and Jonas, U. (2015). Advances in colloidal assembly: the design of structure and hierarchy in two and three dimensions. *Chem. Rev.* 115, 6265–6311.
3. Sacanna, S., Korpics, M., Rodriguez, K., Colón-Meléndez, L., Kim, S.H., Pine, D.J., and Yi, G.R. (2013). Shaping colloids for self-assembly. *Nat. Commun.* 4, 1688.
4. Gerth, M., and Voets, I.K. (2017). Molecular control over colloidal assembly. *Chem. Commun. (Camb.)* 53, 4414–4428.
5. Rogers, W.B., Shih, W.M., and Manoharan, V.N. (2016). Using DNA to Program the Self-Assembly of Colloidal Nanoparticles and Microparticles. *Nat. Rev. Mater.* 1, 16008.
6. Wang, Y., Hollingsworth, A.D., Yang, S.K., Patel, S., Pine, D.J., and Weck, M. (2013). Patchy particle self-assembly via metal coordination. *J. Am. Chem. Soc.* 135, 14064–14067.
7. Elacqua, E., Zheng, X., Shillingford, C., Liu, M., and Weck, M. (2017). Molecular Recognition in the Colloidal World. *Acc. Chem. Res.* 50, 2756–2766.
8. Santos, P.J., Gabrys, P.A., Zornberg, L.Z., Lee, M.S., and Macfarlane, R.J. (2021). Macroscopic materials assembled from nanoparticle superlattices. *Nature* 591, 586–591.
9. Zhang, J., Santos, P.J., Gabrys, P.A., Lee, S., Liu, C., and Macfarlane, R.J. (2016). Self-Assembling Nanocomposite Tectons. *J. Am. Chem. Soc.* 138, 16228–16231.
10. Mitchell, B.S. (2004). *An Introduction to Materials Engineering and Science for Chemical and Materials Engineers*, First Edition (Hoboken: John Wiley & Sons).