The paper will discuss two projects which explore the territory of discrete or digital material organisations in an architectural context. Taking inspiration from the field of Digital Materials, this paper presents an approach to architectural design which is fundamentally "digital" - not just in the process but also in its physical organisation. The use of discrete and digital materials in architecture is argued for from both an architectonic point of view, as well as from efficiencies related to automation of construction. Experiments with robotic assembly are caught between on the one hand the desire to increase speed, and on the other hand increased complexity. This paper argues that robotic assembly on the scale of architecture is only feasible and scalable in the context of digital materials and discrete computation, which has a limited set of connectivity problems. The two projects are a first attempt to translate the concept of Digital Materials to the domain of architecture. The result is an architecture which is digital in its physical organisation. It demonstrates how differentiated, complex and heterogeneous spaces can be achieved with just serialised, discrete elements.

Keywords: Discrete Computation, Robotic Assembly, mereology, Digital Materials, Additive Assembly

FROM CONTINUOUS TO DISCRETE
This paper will discuss two projects which explore the territory of discrete or digital material organisations in an architectural context. The projects are practice-based, and have been developed at Gilles Retsin Architecture, a London based architecture and design practice. They are part of the long term research agenda of the office, and are partially developed in collaboration with consulting engineers Price & Myers. The work also interfaces with academic teaching into robotic assembly at RC4, a research cluster at UCL the Bartlett School of Architecture, as well as with a ongoing research agenda into radical discreteness which has been developed in M.Arch Unit 6 at the University of East-London.

Theorist and architect Neil Leach argues that "while there is clearly a practice of designing that involves the use of digital tools, there is no product as such that might be described as digital" (Leach 2015). Digital design and fabrication tools merely allow a specific type of design to be realised, but they can as well be used for objects which do not appear "digital" or "parametric". This critique ties into a contemporary discussion on the post-digital. The use of digital tools and techniques has matured to such an extent that their use is more critically questioned. So what does it mean for buildings or material organisations to be digital? Can material be organised in the same way
as data? Or is there really no such thing as a digital architecture? Taking inspiration of Neil Gerschenfelds' concept of Digital Materials, this paper will present two projects which are fundamentally "digital" - not just in their design process but also in their physical organisation. In line with Mario Carpo's description of the Second Digital Turn (Carpo 2014), the projects presented understand computational processes as fundamentally discrete. The research proposes to align digital with physical material organisation. Every bit of digital data is the same bit of data in the physical world.

Whereas Carpo only talks about discreteness in the design process, Gerschenfeld's research goes one step further to also argue for discreteness in fabrication (Ward 2010). Essentially, most current fabrication technologies are analogue processes, despite the fact that they are computer controlled. These computer controlled actions mimic human modes of production, they are essentially mechanised artisanal procedures. An industrial robot for example, can be understood as a computer controlled version of a human arm. Techniques such as CNC-milling are actually based on centuries old artisanal methods, just as additive manufacturing is a technique commonly found in pottery. These analogue techniques share the property of continuously adding or removing material - they are continuous fabrication techniques. These tools are computer controlled, but not "digital". The analogue character of computer controlled fabrication tools logically gave rise to a generation of architects identifying as digital craftsmen. These digital craftsmen or makers are essentially not "digital" - they are mere sculptors using analogue techniques in a computer environment instead of in the physical world. Associated with this practice is also the culture of the artisan: a culture of intuitive, small-scale, aesthetic practice. In contrast to this is the Albertian paradigm of the architect as a the anti-craftsman, in communication with the building site only through notation and instructions (Carpo 2011).

The projects presented in this paper extend Carpo's understanding of the Second Digital Turn, by arguing for a discreteness both in the design and in the physical organisation of an object. There are not only philosophical reasons to explore this proposition, but also a series of more pragmatic concerns. Continuous systems have fundamental problems with transitions of material, require a lot of time to compute and fabricate, are less adaptive and not reversible. Moreover, in architecture, it is hard to calculate the cost of continuous systems, as they are not suited to the increased discrete character of workflows such as BIM. Discrete construction systems are generally dry and prefabricated, which means that they can be constructed faster and with more precision (Knaack 2012). With an increased interest in automation of the construction industry, discrete building blocks can significantly speed up robotic assembly process (Gerschenfeld et al. 2015). This paper argues for discrete systems as an efficient method to design, fabricate, automate and build on the scale of architecture.

**DISCRETENESS AND AUTOMATION**

There has been significant research into automation of the building industry. Moreover, there is a historical relation between architecture and machines for building. Vitruvius treatise *De Architectura*, contains one book solely devoted to machines. The mechanisation and industrialisation of architecture was of course also a dream of the modernists, and has recently again gained momentum as a result of increased access to robotics. The most prolific attempt for automation is probably large scale additive manufacturing or 3D printing. Key precedents here are Khoshevis Contour Crafting process and Enrico Dini's D-Shape printer. The main interest in automation of the building industry lies in the promise of increased speed, simplicity and reduced human labour on the building site. However, the previously mentioned attempts have had only a limited impact on the building industry until now. One of the main constraints with large scale additive manufacturing is undoubtedly the speed. Robotic assembly processes should be in principle quicker, as they make use of
larger elements. Advances in process planning and BIM software allow prefabricated modular assembly to become an ultra-fast construction method. For example, the Broad Groups project for a fifty-seven story skyscraper was assembled in just nineteen days in Changsha, China. Moreover, assembly-based processes have the advantages that the components or particles for assembly can be composed of multiple materials. Multi-materiality is a fundamental problem of additive manufacturing processes. Large-scale additive manufacturing is almost exclusively based on a single material. A process which can print at the same time glass and concrete, is hard to imagine, as both materials have entirely different material properties. To produce a complete building, one would still have to use traditional means of construction for insulation, windows, finishes, cabling and so on. Experiments with robotic assembly, and more specifically, additive robotic assembly, have been undertaken by Gramazio Kohler at the ETH. As Gerschenfeld points out, these experiments are caught between on the one hand increasing speed, and in the other hand increasing complexity (Gerschenfeld et al. 2015). Automation of discrete or digital materials can result in both increased speed and increased complexity. However, architects seem to be reluctant to adopt the homogeneous and repetitive lattice-like structures associated with Digital Materials.

**DIGITAL MATERIALS AND DISCRETE FABRICATION**

Although projects such as Gramazio Kohler's robotically assembled brick walls also make use of bricks as discrete elements (Kohler M et al. 2014), technically this has to be considered as a continuous project. Every brick has a highly varied position, which is independent of the geometry of the part. In an analogue or continuous system, a piece of matter has infinite connection possibilities, whereas a discrete or digital system only has a limited number (Ward 2010).

Digital materials are a concept pioneered for mechanical engineering by Neil Gerschenfeld at MIT. A Digital material is a building block with relative local positions which in itself provides geometric constraints for assembly. No plans or tools are required as the parts geometrically define the assembly (Cheung 2012). Digital Materials construct objects which are discrete in their physical material organisation. These structures are reversible: they can be re-assembled into other types of structures. The concept of digital materials also becomes an interesting opportunity for computational methods, as the organization of physical parts is the same as the organization of the digital data. The part computed digitally is also the part assembled physically. The male-female composition of digital materials establishes a binary 0-1 relation between elements. In that sense, a lego-brick can be understood as a digital material. (Cheung 2012.) Gerschenfeld sees their applications in domains as varied as aerospace, building and landscape. Gerschenfeld and his team have developed a number of prototypes of digital materials, most notably the GIK or General Instruction Kit and the Digital Flexural Materials (Cheung 2012; Ward 2010).

The projects presented in this paper are one of the first explorations of the concept of "digital materials" on an architectural scale. Another precedent is Jose Sanchez' Polyomino research at USC, which is based on a game-like assembly of discrete parts (Sanchez 2014). Skylar Tibbits' self-assembling materials are also understood as digital materials. Architectural Digital Materials share the basic properties of the digital materials developed at MIT: they are discrete, have a limited connection possibility with a binary logic, and relative local positioning.

There are some key-differences with the Digital Materials proposed by Gerschenfeld. First of all, architectural digital materials aim for fast assembly, and therefore should be multi-material or multi-functional. Lattice-like structures like the GIK and the Digital Flexural Materials would need a significant amount of cladding to create inhabitable spaces. Secondly, the proposed architectural digital materials have a much larger scale - meters instead of millimeters. The larger scale allows for a much quicker assembly, and responds better to the amount of res-
olution or detail required in day to day living environments or spaces. The use of much smaller units is currently subject of parallel academic research in Bartlett RC4, under guidance of the author.

Lastly, as a result of the larger scale of the digital materials, these also heavily impact the design as a whole. Every vector set out by a single element has a significant impact on the space and structure of the proposed building - in contrast to the smaller scale elements of non-architectural digital materials. If the digital material is small enough, then heterogeneity can be achieved through their assembly - just as a pixel. In this context, Joris Laarmans' Digital Matter Table is a good reference. However, as architectural digital materials are much larger, they need to establish a precise design agency or bias within the component itself. The architect essentially has to embed a series of design decisions in the part, keeping the final building in mind. Digital Materials in mechanical engineering are generally homogeneous and repetitive, and would as such not satisfy the desire for variegated and heterogeneous spaces - which has been one of the driving forces behind the digital.

The design method described in this paper is based on the assembly of cheap, standardized, discrete elements into indeterminate, heterogeneous and differentiated spaces with a high degree of economy. The focus is on a minimum degree of customization for a maximum of differentiation, detail, adaptability and economy. The serialisation and metrology embedded in the pieces allows for efficient robotic automation.

**MEREOLOGY**

The emphasis on the part or bit re-emphasizes the discussion of part-to-whole relations. This notion, which has traditionally been important for architecture, disappeared from the discussions surrounding the digital as a result of an interest in holistic, continuous tropes such as topology and surface. Mereology (from the Greek *mereo* or "part") is the study of the relations between parts and the wholes they construct. Mereology specifically deals with hierarchies in part-whole relationships - a concept referred to as Meronomy or Partonomy (Simmons 2000). Object Oriented Programming has a mereological character through its structure of classes and inheritance of classes. Although mereology is an actual scientific study, developed by the Polish mathematician Lesniewski, it was initially the work of Levi Bryant which was important for the development of the projects below. In the Democracy of Objects, Bryant describes the concept of "Strange Mereology", as a relation where every part is in itself a whole which is not reducible to its parts and where every part is not reducible to the whole (Bryant 2011). This kind of democratic part to whole relationships are typical for Object-Oriented philosophy. It can be argued that Architectural part-to-whole relations are traditionally a non-strange Mereology, which means that the parts are never really autonomous from the whole, but are always reducible to the whole. They have no existence outside of the whole. This non-strange mereological character is typical for top-down design methods, but essentially also for continuous design in general. To establish continuity, every part has to be reduced to a derivation of the whole. A good example of non-strange mereological structures is parametric surface panelisation. In panelisation, every piece is unique, and derived from a specific location on a surface. The large differentiation of pieces requires micromanagement of thousands of components, resulting in excessive labour and energy in assembly. Gramazio Kohler's Programmed Wall, previously mentioned, also falls in this category, as the orientation of every brick is a result of a continuous parametric function. Every brick is rotated in a specific position to establish the overall image of a gradient. This mereological attitude is controversial in relation to the premise of digitally intelligent architecture, which argues for complexity. Often taking inspiration from natural systems such as swarms, digital architects like to argue for bottom-up systems where the whole emerges from part-part interactions. This type of system necessarily requires a democratic interaction of parts and presumes that every part is actually equal, resulting in
a homogeneous population. From the interaction of this homogeneous population, a heterogeneous whole emerges. The use of the term mereology in the context of the work presented in this paper, is mainly notional and pro-forma, merely stressing the renewed importance of part-to-whole relationships and the part itself. At least in the work presented below, it does not directly refer to Lesniewski’s philosophy as a scientific framework.

PROJECTS
Two projects, Blokhut (2015) and Diamond Strata (2016) developed at Gilles Retsin Architecture, start to explore the potential of digital materials in architecture. Both are based on a serialised building block. The first project, Blokhut, still needs some degree of customisation, where Diamond Strata is completely serialised.

**Blokhut**
The Blokhut (2015) is a study for a villa in the Belgian community of Wetteren. The term "Blokhut" is a Dutch for Log Cabin - a hut built of whole or split logs. As a response to budget constraints, and at the same time a request for a differentiated and highly articulated space, the project aimed to extensively use serialised building elements. The Blokhut establishes a differentiated and adaptive architectural system which consists for 90% of serially repeated, discrete, prefabricated concrete elements, and for 10% of unique, customized elements (Figure 2). To test the design method, a large-scale prototype of 2 x 1.5 x 0.3m was developed. It was assembled using more than four thousand pre-cast plaster components, intersecting and joining around a number of customized, 3D printed zones (Figure 4).
The precast component is designed as an arrow-shaped brick, with a male and female connection (Figure 1). This arrow-like connection is able to interlock two bricks together in a fixed position. This discrete building element can be understood as a digital material: it has a relative local positioning, and the design possibilities are defined by the geometry of the element itself. However, the edge of the element has no clear metrology, nor a defined binary connection. This is inconsequential, but allows for some more continuity in the system which helps absorbing some of the issues with tolerance. The discrete pieces in this case are also not reversible, and were joined together with glue and glass fiber. The tectonic quality and structural behaviour of the Blokhut is rather limited, and is further improved upon in the next project, Diamond Strata.

The Blokhut prototype proves that serial repetition of very simple, cheap, prefabricated digital materials is a feasible and accessible method to achieve detailed and adaptable forms. The argument shifts from a system where everything is mass customized, with a labor intensive assembly process, to a limited number of intensive, rule-changing customized zones or glitches and a large number of serially repeated, cheap material. The Blokhut can be constructed without the need for micro-managing thousands of unique, numbered pieces. Instead, the 3D-printed components and bricks set out the instructions for assembly. The assembly is "plan-less" and "tool-less", as the geometry of the pieces defines the aggregation. The finished state of the prototype is undetermined. It can be extended or contracted at any time. The final geometry is messy, redundant and unsimplified (Figure 3).
Diamond Strata

Diamond Strata (2016) is a further development of the Blokhut project, but does not require any customised pieces. The project brief was a multi-family house with three apartments in a rural area close to Brussels, Belgium (Figure 7). The project is an aggregation of a single, beam-like timber element. In this case, a hierarchical digital material was used - a discrete building element with multiple different scales which can cross-connect. The system consists of a linear and L-shaped element with a lego-like male-female connection (Figure 5). The elements can connect through sliding joints on the lateral faces of the piece. The hierarchical system is similar to OcTree optimisation, a procedure used in 3D graphics where space is partitioned with different scales of voxels dependent on the resolution required. Assembly time can be reduced as the scale of the parts is adaptable to the resolution desired.

Moving on from the rather simple and constrained digital materials used in the Blokhut, the elements in Diamonds Strata can act at the same time as brick, surface, column and beam, which improves structural performance. Increased capabilities for parts to interlock and support neighbouring parts are developed, introducing patterns of structure in the system. Two types of pieces are used: an L-Shaped element and a straight piece. The L-shaped element allows the system to grow in all directions (Figure 6). None of the elements have to be customised. The beam-like character of the piece allows for a more efficient and hierarchical structure than in the Blokhut. Central columns and beam-like patterns can be developed first, using the large scale of elements. Afterwards, smaller scale elements are used to bridge between the structures aggregated in the first iteration. The digital materials in this case are made of Laminated Veneer Lumber (LVL), with steel plates for the joints. The fibre direction of the LVL plates is aligned along the long span of the digital material. The elements in this case effectively operate as lego-like pieces, which have to perform efficiently both as column, beam or brick. The inside of
the elements is hollow and reserved for services and cabling.

The resulting building is highly differentiated and complex, however none of the elements are customised (Figure 8). The complexity is based solely on part-part relations. The parts are not reducible to just parts of the whole, and as such also have an existence and relevance outside of the proposal for this multi-family residence.

6. TOWARDS DISCRETE ASSEMBLY

Robotic assembly is only feasible and scalable in the context of digital materials and discrete computation, which has a limited set of connectivity problems. The high degree of serial repetition in the projects presented make a robotic assembly process more feasible. Parts are organised in a grid or voxel-like pattern, the connection between elements is repetitive, and the connection problems themselves are always discrete, neighbour-neighbour or part-part problems. In contrast to projects based on continuous variation, these projects can be fabricated through very simple, serialised actions. The elements' weight has to be limited to 150 kg to be feasible for assembly with large industrial robots. In the case of the proposed projects, assembly could be done with a gantry robot. This gantry robot could assemble chunks or parts of the building off-site, which can then be transported to the site on a normal truck. The inherent disadvantage of this method is the lack of scalability: only one gantry robot can be used at a time. The previously mentioned hierarchical digital materials used in the Diamonds house take into account a certain degree of scalability, so a gantry structure could be feasible in this context. Distributed robots would become more desirable if the scale of the elements would be smaller, but bring more constraints for the design. Next iterations of work should look into material efficiencies and structural optimisation. Further research with robotics could test assembly sequences and optimise the proposed geometries for robotic handling.

This paper presented a series of arguments for the use of discrete and digital materials in architecture. This arguments come both from a architectonic reasoning, as well as from an increased in-
terest in efficiencies associated with automation of construction. The proposed method was tested on two case studies for practice-related projects. The projects presented prove that serial repetition of formally very simple digital materials is able to achieve complex and articulated designs. The projects presented articulate a case for a new kind of digital architecture - which is physically digital, not just in the process. This architecture is fundamentally non-analogue, and non-craft based. It offers a counterpoint to Neil Leach's argument that there is no such thing as digital design. It also expands the scope of the digital beyond its bias against standardisation.

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