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The Benefits of Component-Based Architecture through the Example of the North House

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ABSTRACT

The North House is a proof-of-concept solar-powered home designed for northern climates, intended for the research and promotion of high-performance sustainable architecture. Led by faculty at the University of Waterloo, the development and design of the project was born out of a broad collaboration between faculty and students at Waterloo, with Ryerson University and Simon Fraser University. The North House prototype competed in the U.S. Department of Energy's Solar Decathlon in October of 2009.

This paper identifies the North House as a component-based building. It explains and illustrates the systems of components that make up the North House, and their functions. The paper then explores the possibilities afforded by component-based architecture including adaptability, and demountability. Drawing on this, the paper projects future ways of designing buildings both sustainable to manufacture and operate.

1. INTRODUCTION

North House is a proof-of-concept solar powered home, designed for Northern climates. It is the product of the work of a large team consisting of student and faculty members from the University of Waterloo, with Ryerson University, and Simon Fraser University. The Primary Investigator for the project was Geoffrey Thun, a professor of Architecture at the University of Waterloo. While many of the concepts described in this work were developed by this large team, the production of the descriptive illustrations the identification of the component systems that comprise the house, and the prioritization of a design for disassembly approach to the North House are my own contributions.

In addition to its focus on high-performance architecture, and responsive systems, North House was designed for use as a public demonstration project, where it could showcase a wide range of new applications of technology and promote an energy conscious lifestyle. It was also intended for use as a research laboratory, for the long-term monitoring of its systems, and to house subsequent iterations of these systems. The prototype home was constructed in Toronto by a custom millwork manufacturer, but traveled to Washington DC to compete in the 2009 Solar Decathlon, an event sponsored by the United States Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). In October 2009 twenty teams erected their houses on the National Mall during a seven day assembly period, after which they competed against one another in ten contests structured to both qualitatively and quantitatively assess their design and performance. The teams were given three days for disassembly.

Much of the design of the components that comprise the North House was heavily influenced by the limited assembly and disassembly time allotted by the Solar Decathlon competition, and the necessity for the building to be fully reassembled in a new location. It was also designed with the potential for mass production and mass customization in mind, insofar as its constituent parts might be reconfigured to produce a range of housing types, and sizes. This possibility was explored through the *Latitude Housing System* developed by research based design practice RVTR in parallel with the North House. In addition to describing the component systems of the North House, the following research aims to broadly apply the strategies used in the fully demountable architecture of the North House to the building industry, and to anticipate ways that demountable, component-based buildings may be able to create buildings that are more sustainable to manufacture and operate.

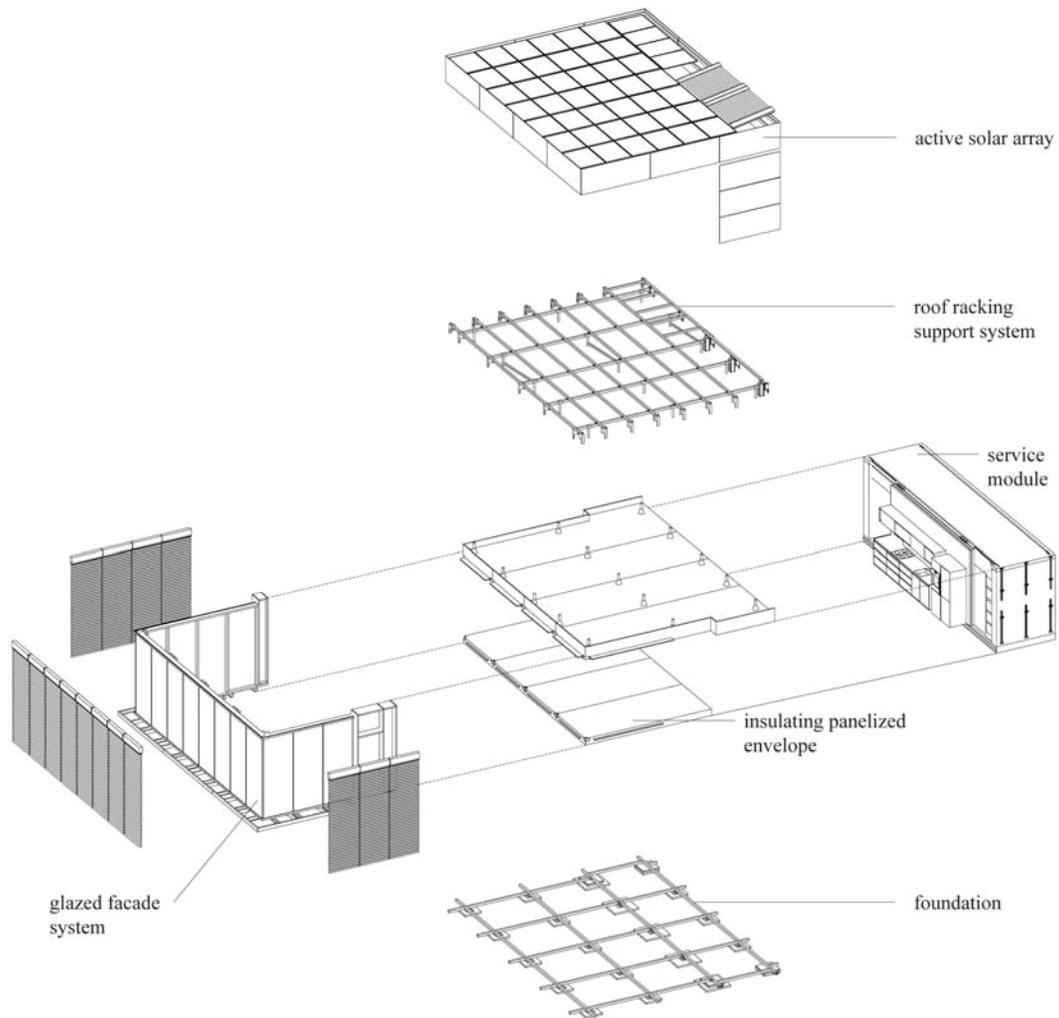


Figure 1: Component Systems of the North House

2. SYSTEMS OF COMPONENTS

The North House prototype is comprised of approximately 480 independent components, not including fasteners. It can be assembled in less than seven days, and disassembled in two days. The typical American House consists of more than 40,000 parts which come together, over a period of months, at a site to which they are anchored (Kieran and Timberlake, 2004). Building components can be manufactured simultaneously rather than sequentially, and can be connected along a series of joint lines, rather than being inseparably intertwined. Kieran and Timberlake (2008) refer to this type of organization as *quilting not weaving*. The separation of these systems allows them to be ‘loose fitting’ and to have some design independence from one another. This technique of ‘quilting’ was important to the design of the North House because of its ambition to be used as a laboratory to test the long term performance of its systems and to test alternate systems.

The components of the North House are organized into a group of distinct systems, which although functionally complementary, remain spatially independent of one another. These systems are: **the foundation, the service module, the insulating panelized envelope, the glazed façade system, the roof racking support system, and the active solar array.**

2.1 Foundation

The foundation system for the North House was designed for the site constraints of the Solar Decathlon and can be replaced to suit subsequent sites. It is composed of: cribbing pads, adjustable scaffold feet & steel substructure.

These three sub-systems of components each serve the requirements of the Solar Decathlon competition in a different way. Plywood cribbing pads of various sizes and thicknesses ensure that the maximum allowable bearing pressure of 1500 psf is not exceeded at any point under the building. Off-the-shelf scaffold feet accommodate variations in grade up to 24”. The threaded rod portion of these scaffold feet comes in various lengths and can be cut to length on site. Steel plates between the scaffold feet and the cribbing pads ensure that the thin bases of the scaffold feet did not cup or sink into the plywood. The steel substructure under the service module and the insulated floor panels serves to increase ease and speed of assembly in two ways. Underneath the service module, the steel substructure ships pre-attached, extending beyond its edges to provide a sturdy frame onto which the craning shackles can be attached. Under the floor panels, the steel substructure is stick framed on site, but sped the assembly process as it can be leveled with ease in advance of the arrival of the floor panels which it supports. These panels can quickly be craned into place as they already had a level base on which to rest. Similar to the *Loblolly House* designed by Kieran Timberlake, the leveling and squaring of the foundation layer of the building is the only step that needs to accommodate site variance. Once the substructure frame is installed and level, assembly can proceed with increased dimensional certainty and speed.

2.2 Service Module (Densepack)

The service module of the North House, or *densepack*, is the single most important and most complex component of the house. It houses the vast majority of the mechanical and electrical systems, wet services and storage, within a highly insulated enclosure. It is the anchor and reference point used for placing subsequent components during assembly. It is the modular base onto which flat-pack components can be affixed. This strategy was born out of transportation constraints. The densepack was designed as the largest unit that could ship on a single truck from Toronto to Washington DC without any special permitting. It must be shipped on an extendable double drop trailer. It houses many of the most complex, time-consuming-to-assemble and delicate systems of the house (mechanical, plumbing, electrical & controls) and by being transported in a single piece both allows these systems to be preassembled and protects them in shipping. In addition to providing structural anchorage points for all other systems of the house, the densepack also provides electrical and plumbing connections, and wiring within the floor and roof panels literally plugs into the densepack. Supply and return air vents are located on the wall of the densepack facing the main living space, as is the main touch screen for controlling the home. Various types of brackets to hold exterior and interior finishes are also pre-installed as part of the densepack.

2.3 Insulating Panelized Envelope

Based on shipping dimensions, the floor and roof of the North House are each divided into four panels. All eight of these panels ship stacked in a single 53-foot flatbed truck with a retractable cover called a “roll-tite”. This allows panels to be craned directly from the truck into position. Each panel has two threaded receivers in either side where large eyelet bolts for the craning shackles can be attached. There is a gasketed tongue-and-groove connection between panels, which helps to position them, and to prevent air leakage between components.

In addition to the challenge of creating a weather-tight and highly insulative roof assembly, all four roof panels needed to act structurally as a single diaphragm, which made the connection between panels a particularly challenging detail. While the north end of the roof panels rests on the densepack, the south end is supported by columns. Two HSS steel lintels, embedded in the ceiling structure of the densepack, are used as anchorage points for the roof panels. On the two outer panels a steel hook, fastened to the underside of the panel drops into a hole in the HSS and secures the panel to the densepack as it is slid into place. At the joints between panels, a steel rod welded to an angle bracket is bolted to these lintels. As panels are slid into position, these rods sleeve into holes in the sides of the panels. Through the unsupported section of the roof, threaded rods run through entire panels and terminate in the perimeter structure of the adjacent panel. This occurs at two locations per panel. This serves to pull the panels together, ensuring that they act structurally as one. The roof panels also provide the connection point to the roof racking support frame, which connects to the roof panels outside of the insulated envelope at 15 sleeved and bolted connection points.

2.4 Glazed Façade System

Other than the highly insulated densepack walls, floor and roof panels, the remaining envelope of the North House consists of the a glazed façade system called the Distributed Responsive System of Skins (DReSS), a sophisticated responsive envelope system which will not be described in detail here. The components of the DReSS system are: Douglas fir mullion frames, a base support frame (to support the sill of the insulated glazing units), insulated glazing units (IGUs), operable ventilation panels, and friction-fit mullion caps, head and sill pressure plates, and automated exterior Venetian blinds.

This façade system provides floor to ceiling glazing on three sides of the main living space of the North House. The Mullion frames are mechanically fastened to the edges of the floor and roof panels. The base support frame is mechanically fastened to the edges of the floor panels and supports the mullion sill. The IGUs are then held in place against the wood mullions using a friction-fit clip system. The system is finished with fiberglass pressure plates at the head and sill, which are concealed by aluminum powder-coated cover plates. At the head, a self-healing peel-and-stick air and water barrier, one side of which is pre-adhered to the roof panel, is lapped over the face of the IGUs and then passes under the fiberglass pressure plate. All of this is then covered by a second large aluminum cover plate which finishes the edge of the roof as well as the head of the glazing system. Insulated ventilation panels and an entry door fit between the glazed façade system and the densepack, introducing an increased dimensional tolerance between the two systems.

The last part of the system is the automated exterior Venetian blinds, which descend from the roof racking structure and control heat gain through the glass. While they are functionally part of the façade system, they belong equally to the roof mounted electrical system. The associated wiring and controllers for these blinds are mounted to the roof racking structure, in a way that is similar to the building’s active solar array.

2.5 Roof Racking Support System

The roof racking support system is separated from the insulated building below. Five HSS racking frames running North-South connect to the roof panels at fifteen sleeved connection points. These create a 30 inch clear space between the drainage plain of the roof and the underside of the solar panels allowing ample access to all roof mounted electrical systems. This also provides space to run outdoor wiring, and ensures adequate air circulation around the solar panels to prevent overheating which can lead to decreased efficiency. On top of these frames, HSS purlins run East-West and provide bolting locations to attach the solar panels. Custom end brackets on both the roof racking frames and the purlins allow for the attachment of the exterior blind supports and the Building Integrated Photovoltaic (BIPV) cladding supports. Specialized brackets are pre-installed onto these supports, receiving the exterior Venetian blinds and the BIPV cladding panels respectively.

2.6 Active Solar Array

The active solar array consists of both vertically mounted BIPV cladding panels and horizontally mounted monocrystalline photovoltaic panels, as well as roof-mounted solar thermal collectors. The roof-top solar array is composed of 46 photovoltaic panels. Four custom designed brackets are pre-installed to the underside of each panel which allow the panels to be mechanically fastened to the purlins below, and minimize the gaps between panels to allow for the maximum roof area covered with active solar cells. Once a panel is in place, the brackets are bolted to the purlins below. The BIPV cladding panels contain back-side contact monocrystalline photovoltaic cells. These lock into the brackets installed on the fascia cladding supports and provide a frameless mounting system for the panels. A special hoist was designed for the Washington installation of these panels as they are very heavy and delicate. This hoist sits atop a lift of scaffolding and contains a pulley which is used to hoist and stabilize the panels during installation. While the exterior Venetian blinds are not technically part of the active solar array, they are installed just behind the BIPV cladding panels, and are completely hidden by them when in the retracted position. Like the BIPV cladding panels, the exterior Venetian blinds are mounted to a steel support panel which includes pre-installed specialized brackets to hold the blinds.

3. BENEFITS OF COMPONENT-BASED DESIGN

3.1 Comparative Monitoring

Expanding on the built proof-of-concept prototype, the component-based design of the North House invites the potential for individual building elements or entire systems to be replaced for comparative monitoring. The current iteration of the North House could act as a control or baseline for monitoring the building's performance, against which any modifications would be tested, enabling researchers to provide concrete comparative data of a type that is normally very difficult to measure from built projects. This is possible because of the North House's capacity to be quickly adapted, and because those adaptations can be easily reversed. This research would offer valuable data to the building industry and it would also allow researchers to compare the predictions of energy modeling with real world findings. By comparing data generated by digital modeling software used to assess the building's performance such as TRNSYS, ESP-r, EnergyPlus, ECOTECT, WINDOW, THERM5 and WUFI, with data gathered from the long-term monitoring of the house's performance, one could gauge the accuracy of the software used, and identify discrepancies between digital and constructed conditions. During the design development phase of the North House project, many option studies for the curtain wall system and the exterior shading device were investigated. In the future, these, and other alternates can be tested using the North House prototype. Solar technology is evolving quickly, and new products are coming to market all the time. Likewise, it is also possible to replace the active solar systems as more efficient ones become available. According to the National Renewable Energy Laboratory (NREL) the efficiency of the best research cells have increased from 27.6% in 1988 to 40.7% in 2008, (NREL, 2009) a trend that is expected to continue.

3.2 Adaptability

The adaptability that component-based design allows has wide applications outside of its facilitation of research. As a residence, North House could expand or be reconfigured to meet the changing needs of its occupants. Additional rooms, for example, could be added to the prototype to accommodate families with children, or individuals who want space to work at home. Similarly, these additions could be removed if the extra space was no longer required. This also makes the building more suitable for adaptive reuse. Replacing individual components allows for easy repair of damaged or outdated components or systems, without causing damage to any adjacent parts of the building. This allows for more efficient and cost effective building retrofits, which could play a key role in enabling buildings to operate efficiently throughout their life-cycle. Adaptable buildings are sustainable buildings, because they have the ability to evolve along-side their inhabitants and to be retrofitted in order to maintain a life-long efficient performance. This ease of repair and reconfiguration will aid it extending the life-span of buildings.

3.3 Demountability

125 tons of renovation and demolition waste is produced each year in the United States. Unfortunately, only 20-30% of this waste is currently recycled. The amount of building-related waste is so great that in the U.S. it is estimated to be roughly equivalent to the volume of municipal solid waste landfilled annually (Lenssen and Roodman, 1995). It is imperative to maximize the portion of this waste that can be recycled, as this would not only prevent valuable resources from being sent to landfill, but it would also decrease the need for raw materials to be extracted and processed. The use of recycled and reused materials saves energy and produces fewer greenhouse gas emissions by reducing the required resource extraction, manufacturing, processing and transportation (EPA, 2010). Designers' awareness of these issues is crucial, as design is the stage where there is the greatest opportunity for effecting change. According to a report prepared by the US Environmental Protection Agency (EPA) the biggest obstacle to effective deconstruction of buildings lie in the initial design. Today designers employ building techniques which make disassembly and material reuse difficult, and typically fail to specify reused and recycled products, resulting in a very limited market for recovered materials (Powell Centre for Construction and Environment, 2010). Designers have the ability to implement changes that are both relatively simple and inexpensive, and will effectively result in a significantly greater instance of building deconstruction and material reuse. While still very uncommon in the building industry, Design for Disassembly (DfD) is a practice that is growing in popularity in product design. In Germany and Japan legislation is already in place requiring manufacturers to consider a design which allows components to be separated for efficient recycling (German end-of-life vehicle act, 2002 & Japanese end-of-life vehicle recycling initiative, 1996). The greatest hindrance to effective recycling is the inability to separate different materials from one another (Braungart and McDonough, 2002). This often leads to an energy intensive recycling process with the recovered material being of a significantly lower quality than the original materials, or to the materials being discarded altogether. In addition to DfD legislation, Extended Producer Responsibility (EPR) makes producers responsible for the entire life-cycle of their products, further increasing the incentive to create products which are easy to reuse and recycle. There are historical precedents for demountable buildings but they are relatively few, and are mainly used for applications of exhibition, as in the case of the North House, or for other temporary uses such as resource extraction, disaster relief or military applications. But beyond particular applications where disassemblable structures are demanded by their program, all buildings could benefit from the designers' consideration of their end-of-life scenario, whether for the whole building or any of its constituent parts.

There are building precedents which address design for disassembly: Buckminster Fuller's *Dymaxion House* provides an interesting example. The original 1927 design was intended for mass production and Fuller proposed the houses could be rented by their occupants from the supplier who would service the building throughout its life. Eventually the house could be disassembled and its component parts returned to the manufacturer for recycling or reuse (McHale, 1962). This early example anticipates Extended Producer Responsibility (EPR), a practice which is only today beginning to emerge. A recent project which builds on these ideas is Kieran Timberlake's *Cellophane House*. It too focused on a holistic approach to the life-cycles of materials, speed of on-site assembly, and design for full disassembly. *Cellophane House* is made up of an aluminum framework into which both panelized and modular units can be inserted, and is rigorously detailed to facilitate separation of components for reuse or recycling. This practice has been referred to as "temporarily held assembly" as opposed to "permanently fixed construction" (Bergdoll, 2008).

Recently, a few projects have been completed with the specific goal of facilitating building disassembly and materials reuse. In 1998 the Canada Mortgage and Housing Corporation (CMHC) published a manual, *Designing for Disassembly* by Vince Catalli. The work was born out of his firm's undertaking to deconstruct a 6000 square foot residential building and salvage all suitable materials for reuse. From this exercise, Catalli generated a series of new building details that required only slight modifications from conventional construction practices. A similar project was undertaken by the EPA in 2003, deconstructing a house and reusing as much material as possible in a building constructed on the same site. Included in this project was a study comparing the cost of the building's deconstruction to the cost of its demolition. Surprisingly it concluded that if there are no hazardous materials present, the cost of deconstruction can actually be slightly less than the cost of demolition, even before considering any revenue generated from recovered materials (Powell Centre for Construction and Environment, 2010). The EPA also funded the *DfD Case Study Home*, a new building designed to facilitate disassembly and adaptive reuse. This design featured repositionable interior walls, and a disentangled HVAC system, meaning that it was not embedded inside walls, and was thus easily accessible. A growing number of examples of this type should provide

adequate encouragement for designers to seriously consider design for disassembly, as well as to recognize the viability of incorporating materials from existing buildings that would otherwise be demolished and landfilled.

3.4 Design for Disassembly Qualities of the North House

While the North House was not designed with the eventual dismantling and recycling of its components as a primary priority, it does satisfy many of the guidelines that have been established for DfD:

All connections are completely reversible. Bolts and screws were used instead of nails, and in special circumstances, other types of reversible connections were used. This includes threaded and sleeved connections between roof panels, friction fit mullion caps, a spring loaded connection for the closer panels, and plug-in electrical wiring. All of these connections can easily be accessed, and can withstand repeated disassembly, leaving components in a suitable condition for reuse.

Components are made up of simple sub-assemblies. Many components of the North House are very simple, for example the substructure and footings, mullion frames, roof racking steel, base support frames and aluminum closer panels, are all essentially made up of a single material. Alternately, many of North House's complex component assemblies could be reused without the separation of their sub-assemblies. Examples of this are the solar panels, IGUs and exterior Venetian blinds.

Systems are disentangled from one another. The systems of the North House remain largely independent of one another. This is also true of the mechanical and electrical systems. The mechanical system is located almost entirely within the densepack and is easily accessed through removable ceiling panels. All wiring on the living space ceiling is surface mounted, and wiring for the solar array is exposed and accessible, making it easy to remove, alter or replace.

Other aspects of the North House's design, however, are not in keeping with some of the guidelines proposed for DfD, and could present obstacles to material recovery and reuse. Problematic elements include the house's more complex components such as the floor panels, which in addition to combining structure and insulation, have the finish flooring nailed in place, making it and the phase change material below difficult to remove. The roof panels and the densepack combine different materials in ways that make them similarly difficult to separate. It is also worth noting that not all the materials chosen for the house have high recycled or recyclable content. Overall, North House meets the majority of the design for disassembly principles, and many of its components could feasibly be reused or recycled at its end-of-life.

3.5 Extended Producer Responsibility

A prefabricated demountable building like the North House which was built primarily by a single manufacturer is a significant step towards factory-made buildings with Extended Producer Responsibility. The key incentives behind EPR (Clean Production Action, 2010) are to promote more sustainable designs, by shifting the responsibility for the entire product life-cycle (especially end-of-life) to the producer, rather than placing that responsibility on the consumer, or the government & municipalities. This is intended to improve the quality of design by minimizing the use of hazardous materials, and materials which are difficult to reuse, and to ensure that materials are used and reused more efficiently. It can also present a valuable economic incentive for manufacturers to find ways to incorporate recycled and reused materials into new products. EPR and product take-back laws are currently gaining in popularity in automotive, electronic and packaging industries. These industries have been targeted for EPR because they create a large portion of the waste stream, and contain valuable and potentially hazardous materials. These are all qualities that they share with building industry waste. If we as designers desire to pursue factor-built buildings, we should consider EPR, and strive to design processes of manufacture that can incorporate existing building waste and create buildings that can provide valuable, useable materials back to the fabricator at their end-of-life.

4. CONCLUSION

The component-based architecture of the North House prototype enables it to function as a laboratory for the comparative monitoring of building systems. It facilitates repairs, and increases the potential for components and materials to be effectively reused at the building's end of life. If we consider the possibilities of mass production and mass customization, the prospect of a component-based housing system becomes more feasible. Repairs would become similar to automotive repairs, where the defective part could be replaced with a readily available spare part, without affecting any adjacent components. Additions or renovations could happen swiftly, adding off-the-shelf components, and returning components that are no longer required to the manufacturer.

Instead of designers aspiring to an assembly line for buildings similar to that of the automotive industry's past, we should look to the future of automotive and product design and design building systems where in addition to being component-based, the components themselves can be disassembled for maximum recycling and reuse. The real design challenge then lies not just in the design of the building, but in the design of its manufacture, and projected lifecycle. Included in this design challenge is the need to anticipate how building materials can be repurposed in a way that provides valuable resources back to the manufacturer or other industrial agents. Through the collaboration of manufacturers and designers on the design of both the building and its process of manufacture, a building product could be created which would be maximally adaptable, giving it a long lifespan, and allowing it to be fully disassembled at the end of its life with the greatest possibility for the reuse and the recycle of its component parts.

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