Architectronics: Towards a Responsive Environment

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Abstract

Contemporary architecture can be seen as a dynamic system that changes in response to its environment and even as a system that can modify itself. Interactive or responsive environments are not totally new to architecture; however, the possibilities in architecture have only begun to be examined. To look at the possibilities in this emerging field experimentation is required and the architect must develop an understanding of the language of sensors, actuators and control systems. This article examines an interdisciplinary design research studio with mechatronic engineers which allowed a wide range of experimentation. It shows that the scope of what can be done with responsive architecture is hard to imagine from where we now stand and that it is only through a broad range of experimentation that we can find the most beneficial uses of this powerful technology. The resulting projects - kinetic architecture on control systems - challenge our understanding of what our built environment could be.
I. INTRODUCTION

1.1. Intelligent Space

Space with an intelligence is an idea that captures the mind of the architect and immediately challenges our conception of architecture. Metamorphosing space has been represented in contemporary media and is becoming more and more conceivable by the technology in common use today. Responsive art and systems that learn are fully possible. The technology of responsive and intelligent space is not new and is accessible to students familiar with digital tools. Engineers are fully capable of designing the technology behind many of the things we can dream up as architects, leaving only the question of what we should imagine.

The design in responsive architecture to a large part involves decisions with regard to programming. What is the spatial or environmental result if a combination of sensors reach determined levels? What should these determined levels be? A change in programming leads to a different space.

Design decisions in responsive architecture include those that must be made with contemporary architecture but also decisions on what should be sensed and actuated, and what combinations of inputs or feedback will cause what kind of actions. Design in this sense is the programming itself: a different algorithm changes the design expression, configuration and behaviour. Different programming then results in different spatial conditions. As such, the programming becomes a powerful spatial design parameter. This direct translation of the algorithm into space is what causes this technology to be so powerful to architects. And yet it is also elusive to define the result; the spatial intent can change by the second: space is always in flux.

The complication of the discussion and the multiplicity of different cases of spatial configurations and overlaps of conditions in the programming cause spatial readings that differ input by input and minute by minute. A different programmer (i.e., architect) could produce a completely different spatial behavior only by the result of their programming decisions.

The term “architectronics” [1] as seen in the title was coined from the combination of architecture and mechatronics; it defines the emerging field of research, practice and design education. Today, through the use of mechatronics, design can be a system that causes change to its environment, or even that can modify itself via information feedback. Clearly architecture need not be static, as it can adapt to changing conditions with a performative feedback loop as its essential aspect. The argument for an architecture on a control system is strengthened when we consider the ubiquitous nature of control systems in our environment: from a thermostat to traffic lights to anti-lock brakes to driver-less public transit. The question of why it is not yet in widespread use in architecture arises: and since it is not in widespread use, there is no well developed idea as to what mechatronics could bring to architecture and, further, what might or might
not be beneficial applications of this technology in architecture. A mechatronic system affords the opportunity for a responsive form of design: one that interacts with environmental conditions, occupancy, input from other systems and even input from prior use.

1.2. Responsive Beginnings and Evolution

It was the mid-twentieth century when the integration of architecture with electronics was first convincingly attempted. Le Corbusier's design of the Philips Pavilion for the Brussels Expo in 1958 provided not only a challenge to the Euclidian tradition owing to the innovative structure of its roof, but also explored new ways of integrating music with visual display and architecture. It resulted in Poème Electronique, a multimedia experience that would currently be termed immersive; the concept combined electronically coordinated sound with a projection system and was timed for the movement of visitors. It involved the installation and coordination of 425 speakers placed throughout the structure. The multimedia design of the building gave the spectators a feeling of being in one performative and dynamic space [2]. A giant model of the atom hung from the ceiling and the sound and imagery premiered to standing room only crowds. At the time keyboard-based synthesizers did not exist, but Edgard Varese’s composition remains today a seminal work in the history of electronic music. When the client approached Le Corbusier to design a Pavilion for the Expo fair, Le Corbusier said, “I will not make a pavilion for you but an Electronic Poem and a vessel containing the poem: light, color, image, rhythm and sound joined together in an organic synthesis.” Perhaps he did; but he was also forecasting the emergence of an age of electronic production, different from architecture in the age of printing.

Figure 1: Phillips Pavilion, Poème Electronique, 1958.
A decade later, the Archigram group illustrated the potential of technology in order to create a new reality, at that time expressed only through images and speculations. As an example (above) Michael Webb’s project offers a seductive vision of a future electronic machine-age dwelling, titled “Magic Carpet and Brunhilda’s Magic Ring of Fire” [3]. It speculated on ultimate interactivity and the possibility of a dynamic fluid and air jet environment supporting a body in space. In 1967 Peter Cook defined architecture as an “intermittently intermeshed series of happenings”. Today the sustainability agenda present in the contemporary architectural discourse brings a new dimension and importance to responsive, interactive and networked architecture and an understanding of architectronics is becoming a prerequisite to the environmentally sensitive design. After all, the contemporary space is able to reconfigure itself in response to human stimuli by addressing dynamically evolving individual, social, and environmental needs.

Apart from a few constructivist projects like Tatlin Tower, the motion in architecture was associated in the past mostly with the industrial or unique building types like wind mill or Farris wheel. Goethe’s notion “Architecture is like frozen music” [Baukunst eine erstarrte Musik nenne][4] was finally brought to rest with the publication of *Kinetic Architecture* in 1970[5]. The book addressed adaptable, or kinetic architecture illustrating it with numerous precedents and it also outlined possibilities related to kinetic building envelopes. It anticipated recent intelligent kinetic systems that started from the convergence of mechanical engineering, computation and kinetic architecture. The winning entry for the 1988 International competition by Jean Nouvel for the L’Institut du Monde Arabe in Paris resulted in responsive, dynamic shades to a relatively unarticulated building. The deployment of 30,000 light-sensitive diaphragms devices on the south facade was to control light levels and transparency. It made the building interact with the changing environment. The subsequent technical problems of the system did not detract from the seminal significance of the building. In recent years, architects have begun to view the envelopes of buildings like some skins of living organisms: enclosures that breathe, change form, and...
adapt to context variations. The design of GSW Headquarters in Berlin is particularly interesting. Two “intelligent” systems assist in providing comfort and energy efficiency in ventilation and shading/ daylighting. Both operate in response to changing climatic conditions with the capacity for user override.

Today interactive, responsive architectural design is proliferating among young designers. The interactivity camp is also aggressively pursuing sustainable objectives through technological and innovative design. Perhaps the closing paragraph in W.J. Mitchell’s Foreward to the recent book Interactive Architecture might serve as a witty reminder of its limits: “So
consider the oyster... Through the evolution of its capabilities, it has already figured out the principles of intelligently responsive architecture". [6] On a more serious note, Bill Mitchell goes further and in his *Smart Cities: Vision* he argues: "It becomes possible to coordinate the operation of different systems to achieve significant efficiencies and sustainability benefits. In designing smart products, buildings, and urban systems we simultaneously consider both their synchronic and diachronic aspects... This approach radically reframes many traditional design problems, and opens up possibilities for new products, services, and business models."[7]

### 2. INTERDISCIPLINARY DESIGN ENVIRONMENT

#### 2.1. Basis for Collaboration

Design of a responsive environment demands that architects understand basic electronics, control systems, sensors and actuators. This is a new discipline of engineering that architecture students must learn. The authors hypothesize that gaining a sufficient understanding and detailed knowledge of this type of technology in order to use it is likely too onerous for most architecture students. However, it could be accomplished by an interactive relationship with mechatronics engineers, who are experts in mechatronics but perhaps not in creating new applications for their expertise. In order to engage seriously in the discussion of the technical requirements of interactivity, engineering students with expertise in mechatronics were included in ROBOstudio[8]: both engineering and architecture students worked collaboratively on research and projects and in this way there was a detailed working knowledge of the requirements, possibilities and limitations at every step in the project.

The goal of the ROBOstudio was to develop a culturally relevant and socially accountable design which included new technical, creative and environmental aspects and incorporated them into a comprehensive design. Design studios in architecture are project-based learning environments guided by the critical feedback of instructors and peers. This design studio methodology is common in architecture, but less common - although equally valuable - in engineering education. By exposure to this methodology, engineering students become able to make judgements on a more global level about their technical decisions and the application of technologies. By working in a collaborative studio environment, both disciplines are challenged to explain clearly their perspective on the design project but also are required to learn and consider the other discipline’s perspective and expertise. This enriches the learning of the students as they see what they understand from a different viewpoint. ROBOstudio was a project-based course offered by the School of Architecture in collaboration with the departments of Mechanical Engineering, Electrical Engineering and Engineering Physics at the University of British Columbia (UBC). The initial goal was to bring together students of architecture and engineering to
explore the possible application of robotics, mechatronics and kinematic structures in architectural projects.

2.2. Pedagogy

In order to introduce students to the new environment, the studio began with a period of research; this introduced the architecture students to the technology of mechatronics and introduced the engineering students to the culture of design. Case studies involving kinetic art, kinetic architecture, mechatronic applications in design and industrial applications of mechatronics were researched. As well, basic theories of control systems were introduced and a database of sensors and actuators was compiled. This short period of research was followed by the two problem sets: the first was framed very tightly in order to limit the design considerations and allow a fluency to develop with the new technology. The second was framed more loosely in order that students could apply their newly-found knowledge to a range of architecture applications. In addition, the projects were framed architecturally so that investigations with the first problem set addressed the issue of essential need, and the second problem set examined electronically-assisted transfigurations and the idea of collective memory.

The projects’ work ranged from concrete problem solving to investigations which were highly speculative in nature, and the students could pursue any combination of digital, wired and/or kinetic models and videos to illustrate their explorations. It became evident early in the studio that the prevailing method of illustration would be video: even in the research, very few case studies were illustrated without use of video technology. This is made necessary by the fact that movement must be illustrated and the most effective way of illustrating movement in today’s digital environment is through video.

2.3. Software

Collaborative work across disciplines in today’s context involves the virtual exchange of information and drawings. Engineering students’ schedules are tight and often require that a collaborative project take place as much virtually as sitting together in studio. This was facilitated by a virtual tool which allowed for shorter and more concise discussions when the students met together in studio: the Virtual Design Studio (VDS)[9], a website through which information can be exchanged in a very visual way, and discussions can occur with fewer scheduling difficulties. The VDS website is a specialized tool which was developed at UBC for the digital architecture studios. It is formatted to allow images to be immediately seen and synthesized. The VDS allows publication of research and presentations directly from the website at each stage of the studio. Research thus can be easily shared among groups and easily accessed as the studio moves into the problem sets. Although the VDS website was not developed as an
application for an interdisciplinary studio, it worked well to facilitate the communication between disciplines and eased the cultural and schedule difficulties which inevitably occurred.

Architecture students were given several seminars on micro-controllers and sensors and actuators in order to quickly increase their understanding of the technologies they would be using. Also, they were introduced to the mechanical engineering software Solidworks and Inventor. In designing moving systems, architects must represent the movement and the change in spatial conditions. This requires software which can represent movement and beyond: in many cases the movement is relative to the next piece and is not unlimited. Mechanical engineering software represents the mechatronic movement well as constraints are built into the software. Constraints allow movement in certain degrees of freedom, for example allowing rotation in the z-axis but not the x-axis or allowing a rotation in one piece to a certain point and then a rotation of a connected piece relative to the first rotated piece. This is particularly difficult with the algorithmic software architects typically use. However mechanical engineering software is more difficult for architects to use and there is a learning curve associated with it.

The engineering and architecture students worked in collaboration to produce drawings, computer simulations, animations, and working scale models of all or part of their designs. Decisions as to what software and what types and scales of wired models would be presented were made on a
case-by-case basis in each project. Just as an architect must decide which software best represents their project or which material they should model in, similarly judgements must be made on what should be wired and at what scale: sensors and actuators, as with many elements in architecture, do not always scale well. As such, decisions must be made as to what actuators would be used for the models versus what would be used at full scale and what sensors would be used for presentation of the idea and how these would compare to the installed full scale sensors. Control systems were similarly discussed. All in all, a whole new set of judgements was brought to the table for discussion amongst the group.

Organization of the studio and companion engineering course was undertaken by three faculty members from the University of British Columbia School of Architecture, two of whom are engineers as well as architects. The students’ progress was monitored through formal and informal review sessions. Specific technical assistance with regard to mechatronics issues was provided by a Teaching Assistant from the engineering field of mechatronics.

In running the ROBOstudio, a clear idea of how the engineering course and architecture studio enhance each other’s learning emerged. The courses, while clearly allowing the students to work in their area of expertise, also facilitate an environment where mutual respect and interaction are developed for the completion of the design. Whereas normal studios and courses address issues within their own disciplines, the opportunity to work in a collaborative environment is challenging to arrange in an academic environment. This studio attempted to offer collaborative learning by setting up an academic framework, with the supporting technical web-based infrastructure required to support the academic endeavour. In terms of computational tools, geometric modelling software like Rhino or 3DStudio was used, while motion models were simulated in Inventor or Solidworks. Programming of controllers, incorporating use of sensors and actuators, was required for the development of the working models illustrating the principles of each project.

3. PS1 SKIN

The initial design project (PS1 Skin) was a retrofit for buildings on campus whose envelopes had problems with their environmental performance. These problems resulted in poor conditions for the building occupants (e.g., inadequate solar control, uncomfortable interior temperatures or lighting conditions, etc.). The buildings chosen were representative of typical building types on and off campus from the time periods in which they were built. The speculative projects completed by the students proposed mechatronic facade systems which responded both to occupation and environment. The students were asked to look at the building drawings and speak to occupants in order to determine what was problematic about the envelope,
and respond with a solution which incorporated technical performance as well as design quality. Developing the responsive building envelope involved design and modelling of a fragment of a building enclosure, sensored to perform. The situated building skin would formatively adjust itself to the dynamic criteria derived from human or environment interactions.

Although the project was situated as a skin retrofit, each building had a specific circumstance that was to be remedied and this related to building exposures and orientations as well as problems with the existing enclosure construction and even such specific issues as building massing and the academic program studied inside. As such, each skin had an individualized and highly customized solution – both customized to the activity within, be it offices, classrooms or labs, as well as customized to sun orientation and envelope problems. The use of mechatronics in many cases gave an advantage to the designers in their ability to be effective and respond to variations in environment and in variations in user requirements and desires, even varying across a very short distance.
3.1. Parasol

This project responds to a laboratory building which is oriented south-west and required that the blinds be fully closed most of the day due to overheating and excessive sunlight. The response to the challenge was to design an exterior sun-shading device that responds both to southern and western light as well as the desire of the researchers for more or less light or views. The responsive façade that was designed had preset programming to track the sun movement and adjusted the shading appropriately for the sun angle; this necessitated change from a horizontal shading device to a vertical one as the sun moved around the project. This adjustment allows the sun to be shaded but the views to the exterior to be preserved as much as possible while the shading is accomplished. The model produced for the project demonstrated the double umbrella mechanical system invented for the project and adjusted mechanically to differing light angles.
Input to the system included sensors for light levels as well as several interior input panels which could allow occupants to control the settings should they wish to override the system by asking for more or less sunlight.

3.2. Swarm Screen

The building façade considered in this example is primarily for south facing offices. Solar gain in the offices was problematic as well as the glare on the computer screens; however, the occupants enjoyed views to the exterior. The solution proposed is a façade made up of simple elements which ‘swarm’ the façade or move around the façade and adjust according to the occupants desire for direct or indirect light and views. The design input to determine the façade’s form at any given time comes from a series of users as well as preprogrammed sun angles and this input is incorporated into an algorithm that defines the curve of the façade lines. Options for the users allow for views, full sun or indirect light only – these requirements for each office are then relayed to the microcontroller which adjusts the screen accordingly. The moving element is a hinged system on linear motors which can move laterally to ‘swarm’ around the building.
3.3. Moiré Active

This retrofit intended to give balconies to students as well as provide a sun-shading device for the overly glazed façade. The balcony system had to meet strict requirements for safety, being a dorm building on the university campus. A full height façade system was therefore selected. This façade mechanically adjusts the relative placement of two thin films to produce a moiré effect — overlapping more when less light is required. As well, the whole system moved around the building tracking the sun such that the least perforated sections were placed in the areas where the sun was directly incident on the façade. The model demonstrated the moiré shift when the light levels increased as well as the movement of the system around the building throughout the day.

4. PS2 TRANSFORMERS

The second problem set (PS2) dealt broadly with the resolution of contested public space by an infrastructural intervention at any scale, be it building, bridge or seat. This problem set was broadly open to students’ initiative but it addressed some aspect of transformation, metamorphosis, disambiguation or shapeshifting. These themes are more common in mythology or science fiction than architecture but have a broad capability of engaging us and are therefore particularly suited to architecture. In a broad sense this process takes place when something undergoes a radical transformation. The electronically assisted metamorphosis of form, or transfiguration is no longer so mythical.
The site was a busy public space with multiple modes of transport and contested space due to its popularity as well as its constrained land area. The site has also undergone change over time, from an industrial site to its current multi-use condition. Each project group was encouraged to take on a use of structure to define space as well as a serious consideration of the interaction with the body.

4.1. Interactive Landscape

A system which responds to input in the form of a direct request by a user is conventionally employed at pedestrian crossings or at a traffic lights when a pedestrian wants to cross. In this case it was used in the design of a robotic landscape. The elements of the landscape move hydraulically responding to user touch. At other times of the day, when a busker performance is scheduled for example, the landscape can be reconfigured into a small amphitheatre or a layout suitable for a market. At other times the landscape could take on the form of a beach, giving much-needed access to the water.
Each of the landscape elements had a touch sensor integrated into its top surface, through which the signal for the landscape block to move was received: up when touched briefly and down when held for two seconds. Multiple safety features were integrated into the design, and the system was typically limited in size to the scale of a step or seat, again to ensure safety. The motion was actuated by a hydraulic system which pumped seawater in or out of the units to modify their buoyancy, resulting in them raising or lowering. The hydraulic pumps could also be activated individually from a central control system. This project crosses many boundaries of disciplines and uses: it is a landscape and/or furniture, it is fully configurable by the occupants or it can be used as art which can be reconfigured based on almost anything. It can be functional on multiple levels and configured as...
pathways, amphitheatre, beach or market. This is a responsive kind of environment which can be modified for different uses or respond to occupation in multiple ways. It does not promote efficiency nor mediate contested space in a conventional infrastructural way.

4.2. Bridge/Ferry

This virtual bridge project produced an infrastructure – both a bridge and a ferry – which mediated between demands for personally powered transportation across a water course with a high navigation clearance requirement (sailboats need to cross under this bridge). This project addressed the contested urban space of a water crossing – where water traffic takes priority over a bridge – through a solution which resulted in the bridge deck being fragmented and floated back and forth on a control system. This could only be possible with sophisticated control system technologies – traditional mini ferries have been working on this route. The advantage this solution has is that it is driverless and uses the energy of the walking/cycling passengers to help power itself: as the passengers bike or walk on the gym-type treadmills, the power is transferred through an electrical/mechanical system to the power system of the unit. The control system is programmed to determine the speed at which the ferry moves based on the energy production of its occupants.

There is a LIDAR (light detector and ranging) sensing system which senses approaching boats and applies navigational rules in its algorithm to determine which vehicle has right of way. Then the controller determines if the vehicle should continue course, speed up or reverse direction. Further levels of safety to keep the ferry on course include a laser light guided pathway as well as GPS tracking of the units. These multiple layers of security are necessary for public safety, which is of major concern when dealing with public infrastructure projects, particularly when they are unmanned. This project deals with infrastructure by mediating contested public space as well as increasing the economy and efficiency of the current system through adding a responsive environment in which people contribute energy and have this registered in the movement of the unit. An infrastructure of this type shows the innovation possible with the application of an architectronic intervention – it produces a hybrid which responds to the dense condition of the site and essentially creates a new type of transportation infrastructure.
4.3. Urban Furniture on Demand

This project developed a fragment of a plaza to transform into a bench when other benches in the vicinity became occupied. This project was in response to a public plaza which at times had a very dense occupancy but frequently lacked seating. In the case when most of the other benches registered occupation, new benches would emerge slowly from the plaza to create additional seating. Correspondingly, as the occupancy of the plaza decreased, unused benches would gradually return to their recessed position. The student involved in this project built a pneumatic muscle to actuate his benches. A pneumatic muscle provides a smooth and safe movement through the use of air pressure, while also offering a slight resiliency or spring in the bench support itself when it is occupied.

4.4. Sun Chasing Transit Shelter

A project which responded directly to local environmental conditions was the transit shelter whose canopy moved along a track to follow the sun. The shelter fragments in sunny weather when rain protection is not required and follows a track, pivoting on a point to face itself to the sun. The site of the shelter is under an overpass, therefore at certain times of the day the shelter fragments are required to distance themselves from the original position in order to avoid shade and seek sunny locations. Under rainy or windy conditions, the shelter fragments return to their original enclosed position. For safety reasons, sensors detect any resistance in the movement of the elements, such as that due to a person being in the way, and movement is halted. The movement in this case is accomplished through a duplicate track system. The first track directs the movement of the individual unit and the second track determines the rotation of the shelter. Through the double track arrangement, the elements can rotate independently from their translation.

4.5. Restaurant Canopy in Flux

Another project demonstrated a responsive canopy for a seasonal outdoor restaurant patio which was activated by movement as well as by local environmental conditions. In this case, the canopy could activate according to local activity under it so that if a person was occupying a table, that table could be shaded or protected from rain, while other unoccupied areas might not be protected – as one walked under the canopy, elements could open up to provide cover from rain. The rain and sun sensors would provide information on current conditions and the algorithm would respond according to programming related to occupation, time of day and year as well as actual sensed environmental information. The response of the canopy is designed through the algorithm used: for example the behaviour of the canopy could depend on whether or not it ‘predicts’ a person’s
movement based on a current trajectory or responds only to the person’s current condition. As well, sun can be dealt with in a multitude of ways: people can be shaded or full sun can be allowed. In this project, the spatial occupation and environmental conditions inform the architecture but there is also an element of improving efficiency as the current configuration of the plaza uses umbrellas to provide shade, so when the weather is rainy, the plaza is abandoned.

4.6. Self Tuning Performance Space

Responding to occupation in a more specific manner, a performance hall was designed to adapt to the required acoustics of the space. The hall was conceived as an infrastructure which could provide a facility able to adapt to the type of venue required, such as a rave cover, an outdoor theatre or an
indoor concert hall. Furthermore, the arrangement of the elements of the hall allowed the interior volume to be modified to alter reverberation time – thus the hall itself could be ‘tuned’. At a smaller scale, interior roof panels were designed to automatically adjust their absorptive qualities, thus further impacting the interior acoustics – primarily reverberation time – of the space. Thus there were two scales on which the acoustic tuning performed.

The control system which was developed has similarities to the popular iPhone app Shazam. The algorithm analyzes sound from a simple microphone receiver, and based on an analysis of the sound sample can then actuate the acoustic control mechanisms. Movement of the theatre elements was based on current movable stadium roof technology. In this project, the multiple configurations of the performance space allow for efficiency in land use and an ability to respond to different programmatic
requirements with a minimal footprint, thus mediating contested urban space. The further responsiveness of this design, in this case to occupation as measured by acoustic criteria, hints at an ability to measure or process simple sensor information in a much more complex way in order to respond more sensitively to the environment.

5. CONCLUSION

Research into the use of mechatronics in architecture only begins to identify the huge potential and range that the field encompasses. Architectronics as a field would encompass scales of design as large as the infrastructure of the city and as small as adjustments in height of a piece of furniture: all use a consistent language of sensors, control systems and actuators. Building scale manipulations are not difficult, as research into stadium roofs, backhoes and light rail technologies demonstrates. This investigation highlights the immense range of possibilities for interactive environments in architecture. The projects undertaken demonstrated a breadth in possible applications of control systems which was previously unforeseen. To narrow the field for further study, it is noted that some of the most beneficial investigations involved applications of mechatronics to sites where more than one program was desired across time, and this transformation of architecture would allow the space to accommodate a variety of uses. Using another methodology to narrow the study, such as focussing on only one economical and simple actuation, would in itself produce interesting investigations. It was noted by the engineers during the course of the study that sensors were inexpensive and actuators were costly, so the more sensing and less actuating that takes place, the more economical the overall system. This type of economic reality applied to architecture could, as shown in other related architectural explorations, result in highly innovative systems and spatial consequences.

Much more investigation into potential applications is required: as in any research, experimentation is required. As we have seen with digital modelling in architecture, significant experimentation with what could be done is required to develop a critical position on what should be done. For now the field is wide open for experimentation and from this experimentation, further benefits will emerge.

References
8. ROBOstudio was an interdisciplinary design studio 2009/2010 held at University of British Columbia http://vds.arch.ubc.ca/vds_ROBOT.

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