A COORDINATION STRUCTURE APPROACH TO THE MANAGEMENT OF PROJECTS

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ABSTRACT

The paper uses object based models to capture and make visible the system level coordination structure of complex projects. These models facilitate the development of a shared view necessary for effective project management. In the paper, development and use of the models are illustrated using examples drawn from the design of custom silicon. We examine three custom silicon design projects to identify the significant coordination problems encountered as well as the difficulties of using activity based project management tools. Then we develop object based models of coordination structure as a tool to overcome these difficulties. We use these models to capture a project manager's view of the four stages of the custom silicon design cycle: design definition, chip design, prototype manufacture, and system integration. We conclude by discussing the relationship between the coordination structure approach and other project management tools, and the managerial advantages of the proposed approach in the management of projects. Because of their simplicity and stability, coordination structure models form a useful front-end for conventional activity based project management. The approach has particular value for the management of projects in which the task structure is complex, uncertain and unstable, as is typically the case in new product development.

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I. INTRODUCTION

The paper develops an object based approach to modeling coordination structure which is useful in the management of projects which exhibit complex interdependencies, high task uncertainty and significant autonomy of the individuals and groups involved. The models take the form of diagrams which make visible at a system level the interdependencies among groups and individuals involved in a project. This visibility facilitates the development of a shared view of the project which is necessary for effective management. The models provide a useful complement to conventional activity based project management and control tools. We ground our explanation of the approach in experience gained during the management of custom silicon design projects.

Coordination tasks typically change over the course of a project's life cycle. Coordination requirements of a complex project are unlike those between units, such as manufacturing and procurement, that interact with one another in a way that is stable over time. In managing and controlling projects, firms commonly use a variety of activity based tools such as Gantt charts and PERT/CPM network models. However, these tools often prove inadequate [6, 20]. In large projects activity specifications become very complex. In projects with high task uncertainty the work breakdown structure is volatile and unstable as well as complex. Complexity and uncertainty limit the usefulness of work breakdown structure and activity based management tools as a basis for project management particularly if the individuals and groups involved can make significant decisions about work processes independently.

The design and manufacture of semi-conductor microelectronic devices has been on a long, continuous and rapid learning curve unprecedented in the history of technology. As line widths and feature sizes approach the 0.5 micron level, electronic systems producers are now able to integrate large systems on single chips. These developments, together with rapid advances in design methodology and CAD systems, have meant that custom silicon design has achieved critical importance in the push for competitive advantage in industries like computers and telecommunications.

Custom silicon design entails the design of high performance integrated circuits most often using silicon as the substrate, in which maximum performance is attained through the use of custom designed circuitry. Custom silicon designs are at one extreme of a whole continuum of integrated circuit design - they push the limits of technology. As a result, custom silicon design projects feature complex interdependencies, high task uncertainty and significant designer autonomy and so were chosen as a context within which to explain the coordination structure approach to project management.

The objective of this paper is to develop a method for representing at the system level the coordination structure of a project that can be used to integrate different parts of an organization to accomplish project goals. The proposed approach allows managers to: i. capture and make visible the system level interdependencies between project participants, ii. assign coordination tasks that fit the changes in coordination requirements over the life of the project, and iii. reuse proven coordination structures. Visibility at the system level facilitates the development of a shared view of the assignment of responsibility and their interrelationships. A better fit between coordination tasks and coordination requirements results in better management of the changes inherent in projects from one stage to another. Reuse of coordination structures leads to reduction in project lead time.

Section II sets the context of the paper with a brief review of coordination and project management. In Section III we outline the cases of three custom silicon design projects to identify typical coordination problems, and the difficulties found in using activity based project management methods to address them. In Section IV we define coordination structure as the entire set of interrelated interdependencies between all of the individuals and groups in some problem domain, and introduce object based models to capture a system level view of coordination structure. In Section V we develop object models which capture the coordination structure of a typical custom silicon design project and show how they can be used to address some of the shortcomings of activity based project management methods. Section VI concludes by summarizing the relationship between the coordination structure approach and other project management tools, and the managerial advantages of the approach in the management of complex projects.

II. COORDINATION AND PROJECT MANAGEMENT

Coordination entails integrating or linking together different but interdependent parts of an organization as they work together to accomplish organizational goals [7, 15, 31, 42]. Research has identified effective coordination as an important factor which differentiates successful from unsuccessful projects. Performance in product development has been linked to a higher degree of coordination around: i. functional units, ii. stages of development, iii. multiple projects, iv. suppliers of technology and components, and v. customers [7, 15, 17, 23, 24, 32, 34, 44, 46, 48]. Many of the most significant problems in the development of complex products stem from inadequate integration of work between groups.

A variety of coordination mechanisms useful for the management of projects have been proposed in the research literature. These mechanisms include: task partitioning to decrease task interdependencies [43]; engineers with broader skills developed through extensive training and job rotation [7, 15, 19, 44]; overlapping engineering stages with early downstream involvement and intensive cross-stage communication [7, 15, 44, 46]; customer driven development [7, 15, 44]; simulations and computer based tools [7, 15]; cross-functional teams [7, 14, 15, 29, 38, 44]; project managers with strong power [7, 15, 34, 44, 46]; clear and widely shared understanding of the product and the project [14, 44]; war rooms where timetables, mockups, process layouts, drawings and related documents are available and all critical meetings are held [7, 15]; speedy cross-function conflict resolution mechanisms [7, 15]; and frequent reviews of the development process [10].

A central theme in outstanding projects is having a system view of the project concept [14, 44]. Implementation of coordination mechanisms by a project manager is directly related to participants of the project having a shared view of the entire set of interrelated interdependencies between all of the individuals and groups that are involved in the project.

In this paper we are concerned with the scheduling of activities which forms the basis of project management defined as "the system of procedures, practices, technologies, and know-how that provides the planning, organizing, staffing, directing, and controlling necessary to successfully manage an engineering project" [40]. We argue that whatever coordination mechanism is used in a project, its effectiveness will benefit from activity scheduling based on a shared view of coordination structure.

Once the objectives for a project have been defined, developing a project schedule traditionally involves the following steps: producing a work breakdown structure of activities to be performed, allocating the activities to individuals and groups, identifying the interrelationships between activities and sequencing them, estimating activity duration and costs, reconciling the schedule with available project timing constraints and available resources, and finally reviewing and updating the schedule as the project proceeds. The five major scheduling approaches used in project management are milestone charts, Gantt charts, full wall scheduling, and the precedence network techniques - CPM and PERT [12]. Milestone charts, full wall scheduling and PERT are based on events which mark the completion of specified activities. Gantt charts and CPM are based on activity specifications directly.

We argue that a system level view of the entire set of interrelated interdependencies between those involved in a project can make scheduling more effective as a basis for project management. This is particularly true for projects in which there is: a) a complex set of interdependencies between individuals and groups involved, b) a high level of task uncertainty, i.e., uncertainty in whether or not a task is necessary, what its precedence relationships with other tasks are, and what its duration will be, and c) a significant level of decision making autonomy for these individuals and groups. In projects with these characteristics, work breakdown structures and schedule representations are complex and unstable. As a result they are difficult to make visible in a meaningful way to the individuals and groups involved in a project and so fail to provide the basis for the development of a shared view necessary for effective project management.

III. COORDINATION OF CUSTOM SILICON DESIGN PROJECTS

We examined three projects carried out in the same product development organization of a major integrated manufacturer of telecommunications products. The firm has a business strategy of being a technology leader and incorporating the capabilities of the most advanced technologies in its products. The development organization creates competitive advantage for the firm by capturing innovative, high quality, manufacturable system designs in silicon. The firm has internal silicon design, fabrication and packaging facilities, although its product development groups can and do go outside for these services. The firm has sufficient resources to develop internally basic design and manufacturing technologies and CAD tools for chip design.

Table 1 provides an overview of the three projects.

Table 1: Three custom silicon design projects

Project	Number of Chips	Internal/ External Technology	Design & Manufacturing Technology	Use of Complexity & Speed Potential of the Technology
A	3	external	1.0 micron standard cell	pushed the limits of complexity & speed
B	1	external	1.0 micron gate array	pushed the limits of complexity & speed
C	3	internal	0.8 micron BiCMOS	used 2/3 of the potential complexity & speed

Coordination Problems Identified

In this section we briefly describe each of the three projects and outline the responses of managers to the question: what were the significant coordination related problems encountered and what were their impact on the firm in terms of unanticipated costs and time delays?

Project A

Project A supported the development of a new telecommunications switch. The project was managed using CPM and Gantt charts. The three chips were application specific integrated circuits (ASICs) to be designed using a one micron standard cell design and manufacturing technology provided by a large external vendor. The firm had been assured by the vendor that this technology was stable. The designers of the firm took this assurance at face value. This became a costly error when the technology's cell library proved inadequate for the purposes of the ASIC designs in the project. In the end, the external vendor worked with the firm on the development of another design and manufacturing technology which was used for the chips in the project. Managing this unanticipated change cost the firm $450,000 directly and 16 weeks in silicon design interval. The consequent indirect costs from delays in software development and other downstream activities was significantly higher than this.

Project A also experienced three other significant internal coordination problems. First, a lack of clarity with respect to responsibilities for the back plane specification cost the firm 3 man months and $40,000. Second, no system architect was charged with overall responsibility for one of the three chips. As a result there was inadequate coordination among the various groups contributing to the development of the chip. The chip had 11 system related bugs, although it "met" its specification. These bugs cost the firm $150,000 and delayed completion of the design by 21 weeks. Third, the bus specification proved to be too complex. The person who wrote the specification was not explicitly coordinating with any other individual or group that was going to use it. As a result no one but the author of the specification understood it. Performance of the system had to be degraded by at least 20 percent because of the resulting misunderstandings.

Project B

The one chip in project B was an average complexity ASIC, again using technology supplied by an external vendor. It was the critical component in a system that had hard customer deliverables and penalty clauses. Project B was managed using Gantt charts. The assumption was made that the design was going to be "easy". The design project looked very good for the first 2/3 of the schedule, but then fell apart. A requirement for a schedule acceleration of several weeks prompted the design team to make what they thought was a simple switch between the vendor's standard cell design and manufacturing technology to the same vendor's gate array technology. The standard cell technology had been put through an approval process by the firm itself. The design team assumed that the gate array technology had also been approved, whereas it had not been. This proved to be a costly mistake. When the switch in technology ran into problems, the lack of a systemic view of coordination made it difficult to assess responsibilities and information transfer for technology choice, and documented performance. The problem caused an additional 8-10 man-months on an 18 man-month project.

Project C

Project C involved the development of three very high performance custom chips using leading edge technology, design methodology and packaging. The project was managed using CPM. A variant of Venn diagrams was also used to map out areas of responsibility. Three significant coordination related problems were identified. The first was caused by not specifying interrelated responsibilities for the computer aided engineering (CAE) environment. This lead to a late start in identifying CAE issues resulting in a direct impact of $425,000 on the project and a delay in design interval of 10 weeks. The second resulted from not achieving a shared view within the project team of cell library performance for the technology to be used, a problem not unlike that which occurred in project A but in this case entirely within the firm. As a result, inadequacies in cell library performance were not apparent early. This caused an additional 2-4 man-months of extra effort in a stressful environment and a direct dollar impact of $46,000. The third problem was caused by a lack of adequate specification of a key circuit in a high performance microprocessor provided by an external supplier. The circuit had been talked about, but neither its attributes nor the interrelated responsibilities anchored around it had been well specified. In the end, this caused the firm eight man-months of new work and a direct dollar cost of $100,000.

Difficulties of Using Activity Based Methods to Coordinate

Managers of the three projects described above used PERT, CPM and Gantt charts to facilitate coordination. There are four reasons why managers of the three projects found it difficult to facilitate coordination using these tools. First, PERT and CPM chart representations do not make visible the interconnections between individual responsibilities and that of the development organization as a whole. When a project ran into difficulties (and all did at some point in time) or when the content of the project changed, there was no integrated system level view of the design process, the design organization, and the chip being designed which facilitated the rework of the work breakdown structure and the reallocation of task assignments.

Second, activity based representations were unstable and for this reason not reusable from project to project. This was a significant barrier to organizational learning. An ex-post examination of the three projects revealed that each had activity work breakdown structures that were very unstable over the life of the project. In project A, tasks took on average two times as long as originally scheduled for. As well there was a 30 percent increase in the number of tasks actually carried out from what was originally scheduled. Project B experienced a 1.5 times increase in average task times and 50 percent new tasks originally unscheduled. Project C experienced a 1.2 times increase in average task times and 15 percent new activities originally unscheduled.

Third, project members relying on activity based process models to coordinate their efforts did not create a shared view of what needed to be coordinated for the project to be successful. They expected a single source of activity specification, one person who has been accepted by all within the design organization to know and understand what needs to be done when, by whom and how. Project managers found this expectation hard to live up to. The main reason for the lack of a shared view of the project was the lack of visibility of activity based PERT and CPM representations.

Fourth, the level of detail involved in specifying a large number of activities as entities quickly led to a loss of perspective for both the project manager and for the project team members. The specification of activities very quickly became complex and granular. Managers found them very hard to use to integrate the efforts of the many participants in the design process. In projects A and C, for example, the CPM and Gantt chart project management methods did not make visible the lack of adequate coordination mechanisms anchored around the technology to be supplied.

IV. DIAGRAMMATIC REPRESENTATION OF COORDINATION STRUCTURE

We argue that a manager can best develop an understanding of a complex project, such as a custom silicon design project, through an analysis of its coordination structure - a system level view of the entire set of interrelated interdependencies between all of the individuals and groups that are involved in the project. Specifying the coordination structure of the project prior to specifying the actions required to manage these interdependencies, and arriving at a shared view of this structure on the part of the project participants, can reduce the structural problem of managing part-whole relationships [41]. Thus, we argue that creating a shared view of coordination structure can increase managerial effectiveness

The ability of individuals and groups to coordinate has been linked with their ability to perceive and manipulate the same common objects [13, 26, 27, 30] or their ability to come to have similar understanding of the objects that they share [14]. This concept of common or shared object is similar to that of boundary object [39]. We build on this work to conceptualize coordination structure using three elements: actors, shared objects and links between actors and shared objects. Actors are the individuals and groups involved in a project. Interdependencies between actors are specified by their links to a set of shared objects. Conceived in this way, the coordination structure of a project can be made visible using diagrams. Participants in a project can work toward achieving a shared view of the coordination structure of the project using these diagrams.

Some analysts have taken an information flow perspective to study projects [1, 7, 15, 25, 28]. While we agree that the analysis of information flow is important for the management of projects, we maintain that there is a more fundamental point of view based on coordination between actors through their links with shared objects. Once the coordination structure of a project is understood, information flows and their related tasks can be analyzed in a more concrete and meaningful way. The shared objects which link two actors form the basis for the content of their interaction. The frequency of communication between two actors without reference to content can be a misleading indicator of interaction effectiveness [2]. Modeling project interdependencies using shared objects is consistent with [13, 26, 27].

Coordination Ensembles

A coordination ensemble [3, 4] is a configuration of actors that interact by creating, modifying and using an array of shared objects. This definition captures the essence of the base layer that underlies the coordination processes involved in a complex project. It focuses on actors' ability to see and manipulate shared information.

We focus on links between actors and shared objects and exclude those between actors or between shared objects. The interdependency between two actors' responsibilities is represented in terms of the shared objects that the actors create, modify or use. A second important characteristic of coordination ensembles is that they focus on system level coordination structure. This highlights the fact that each link must be considered within a whole configuration of other actor/shared object links. This approach is different from those which study interdependencies between actors or objects taken a pair at a time [13]. We emphasize representing the coordination ensemble around objects rather than procedures or data. This is a third important characteristic of our coordination ensembles. Both actors and objects are objects in the sense used in object-oriented analysis and design. Objects are entities, concepts, abstractions or things with crisp boundaries and meaning in the problem domain [35]. An object combines both data structure and behavior in one entity that you can do things to. An object is something that can be distinguished from other objects (has identity), can be characterized in terms of dynamic values of a set of properties (has state), and can interact with other objects (has behavior) [5].

Object based representations appeal to human cognition [5]. Humans find it quite natural. They reduce the gap between the complex real world system and the model used to represent it [18]. The object based representation of coordination provides actors participating in a project with a better appreciation of the critical elements of the project, what needs to be coordinated and how to go about coordinating. It provides a common vocabulary of discourse to effectively communicate the nuances of a project. More importantly, object based representations are more stable than those that are activity or data based [5, 8, 9]. This stability can facilitate organizational and individual learning.

Coordination ensembles are diagrammatic representations. An alternative is to describe a system of interdependencies as text. Larkin and Simon [21] found that in diagrammatic representations, as opposed to textual representations, much of the information needed to make an inference is present and explicit at a single location. Cues to solving the next step of the problem often are present in an adjacent location in the diagram. Moreover, problem solving proceeds more smoothly and requires less search of implicit elements than is the case for sentential representations.

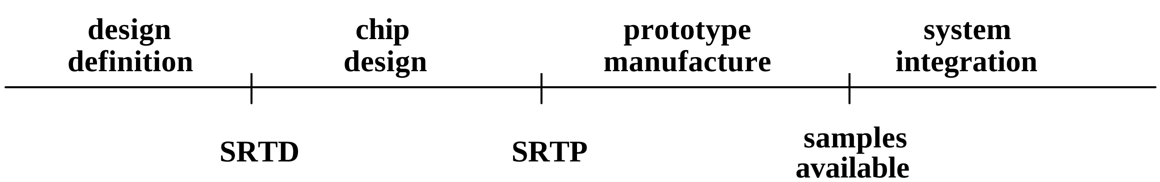
Several authors [5, 8, 9, 16, 22, 33, 35, 36, 37, 45] have specified approaches to object oriented analysis to describe what a target system is supposed to do. We use the approach detailed in [35] because of its elaborate specification of the sequence of steps to follow, greater care placed on identifying and specifying links between objects, emphasis on front-end conceptual analysis, and wide use in industrial object-oriented applications.

V. MODELING COORDINATION STRUCTURES

In this section we illustrate the development and use of coordination ensembles by modeling the generic coordination structure of the custom design process.

We anchor our examination of the custom silicon design process around three important keypoints: silicon release to design (SRTD) which marks the successful completion of a specification for the chip to be designed, silicon release to production (SRTP) which marks the successful completion of a layout which can be used for manufacturing, and sample delivery which marks the point in time when samples are first available for test and system integration. These keypoints mark significant changes in the coordination ensemble active at the time. Thus, we have four stages for the silicon design process: design definition, chip design, prototype manufacture, and system integration as shown in Figure 1.

Figure 1:
The four stages of custom silicon design



Figures 2, 3, 4 and 5 capture the view of a project manager of the generic coordination structure for the four stages of custom silicon design projects based on those illustrated in the three cases. Actors are shown as rectangles and shared objects as ovals. Verbs specify the nature of the links between actors and shared objects. Figure 2 shows the coordination ensemble for the chip definition stage. The chip architect coordinates with the system architect around three shared objects: the product specification, the architecture of the product and the specification of the board on which the chip is to be mounted, in order to produce the chip specification. There are three levels of management involved in this process: a chip manager who operates at the technical level and takes an active role in the development of the chip specification; a project manager who manages the design and development of a number of chips involved in a project and takes a less active role technically in the development of the chip specification; and a program manager who is part of senior management and is charged with overall program direction, resource allocation and linking with other departments.

Figure 2:
Design definition

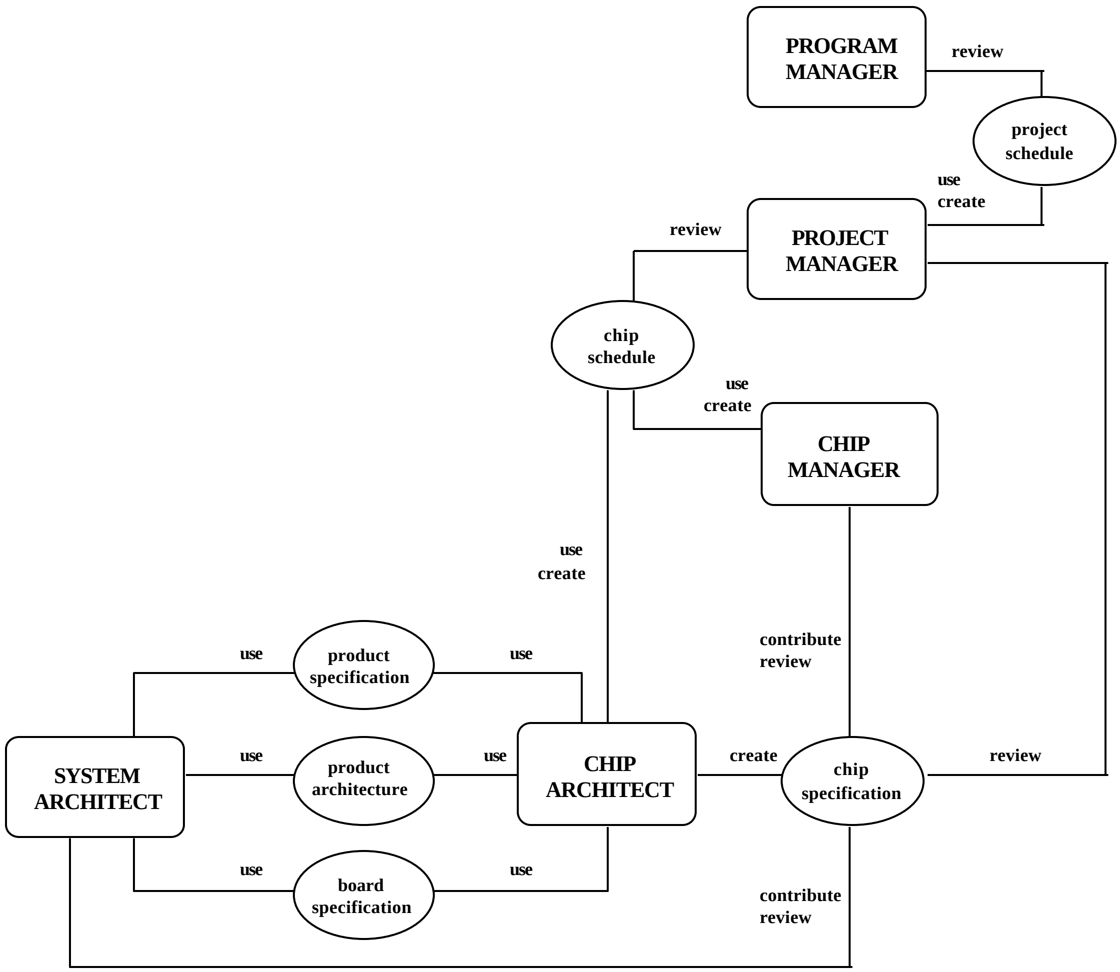


Figure 3:
Chip design

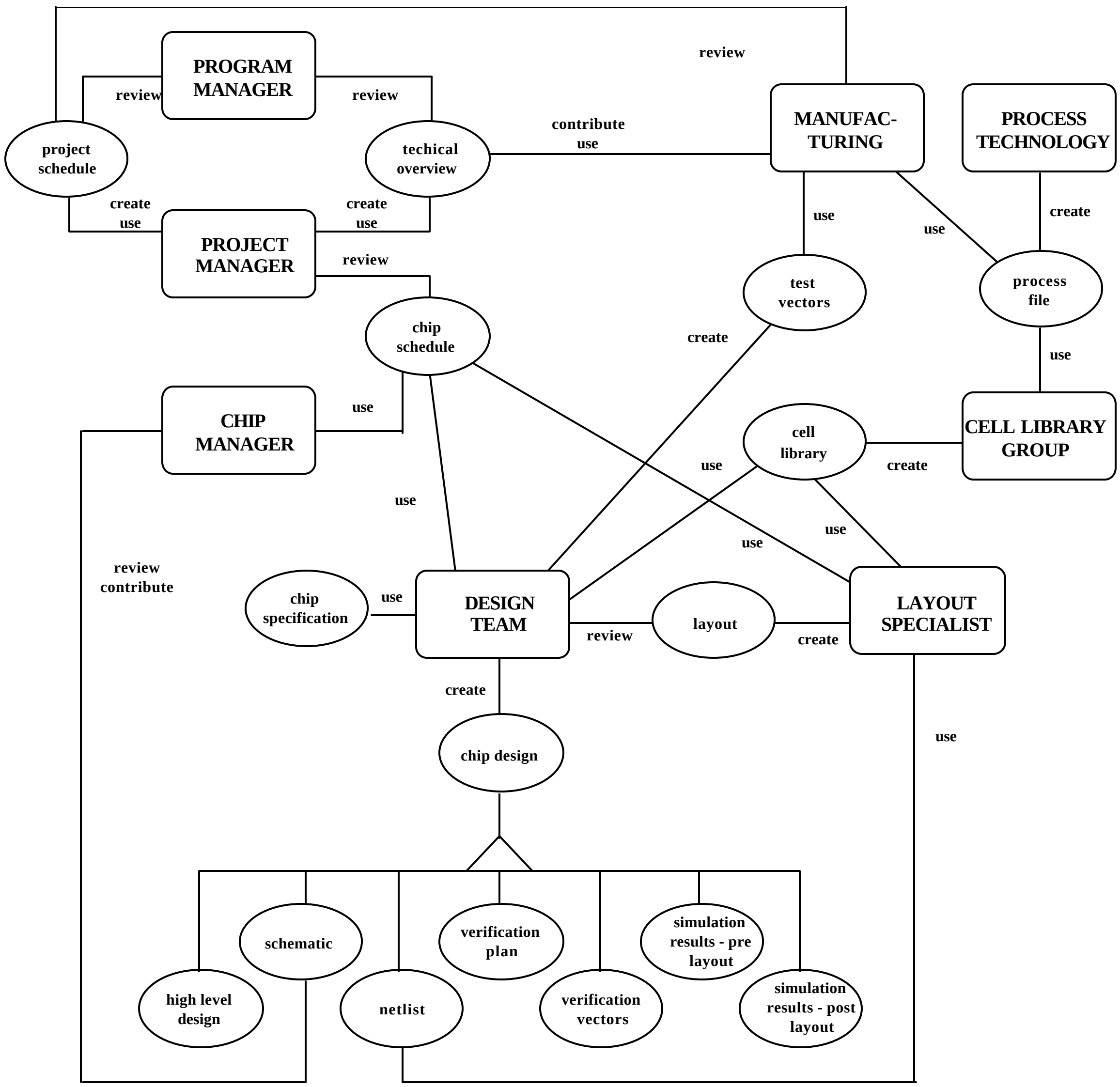


Figure 4:
Prototype manufacture

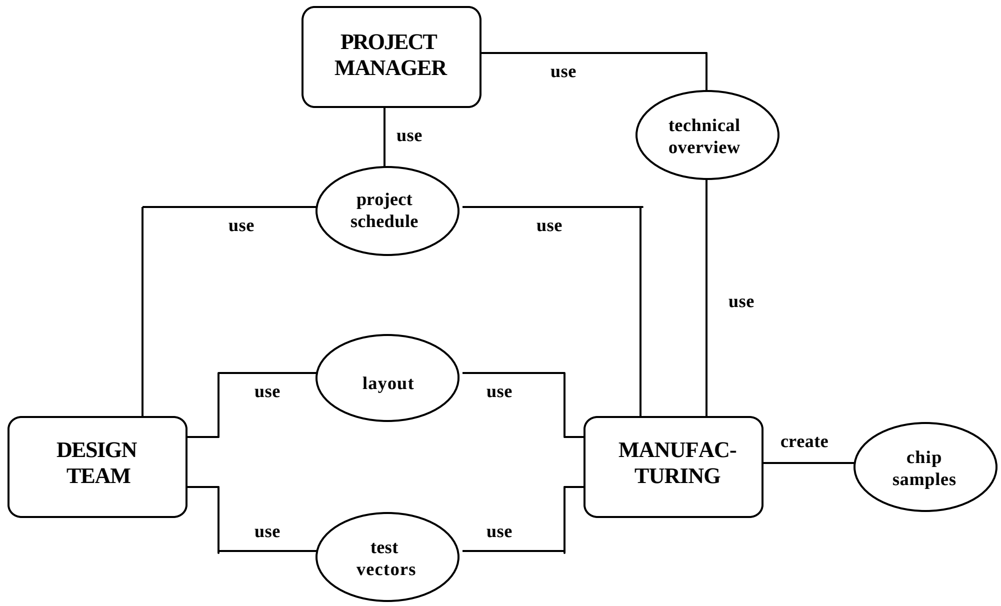


Figure 5:
System integration

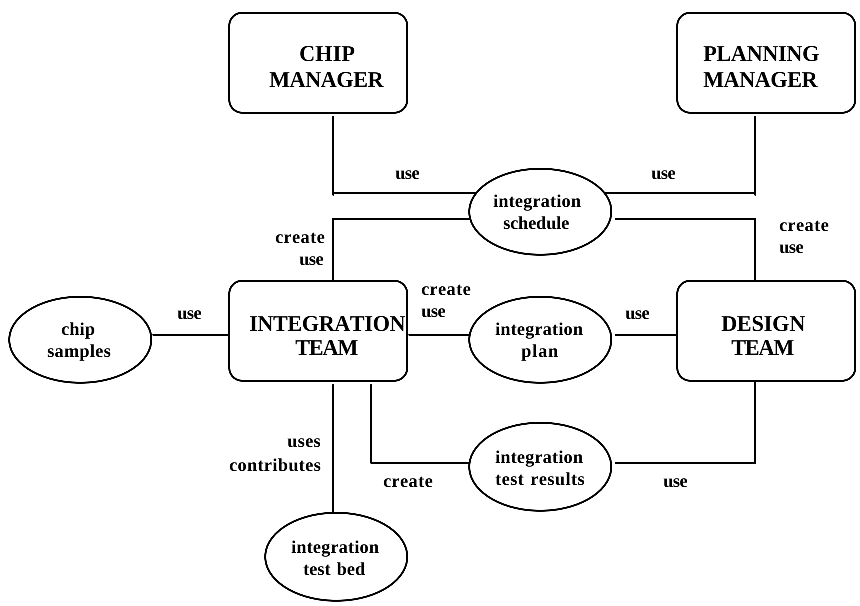


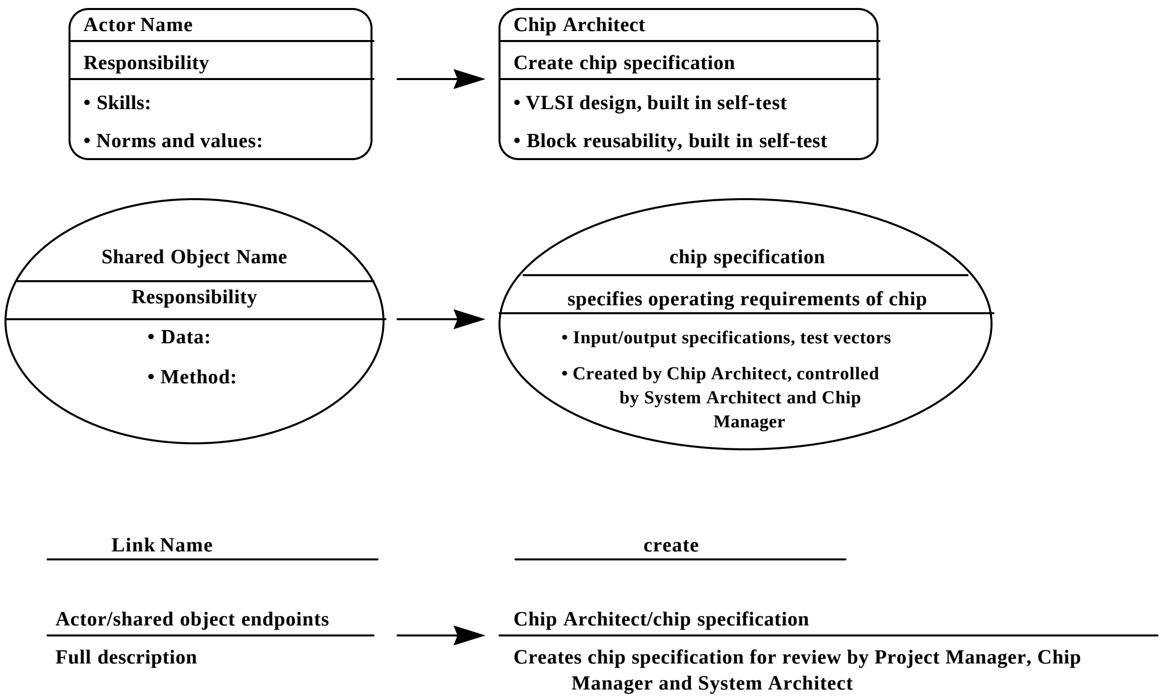
Figure 3 shows the coordination ensemble for the chip design stage of the process. The design team, generally a self-organizing group of 3 to 4 designers, is charged with using the chip specification to produce a layout usable for chip manufacture. It coordinates with a variety of actors including managers, a layout specialist, a cell library group and manufacturing around a variety of shared objects. The technical overview contains the technical demands which will be placed on manufacturing given the current state of the chip design and is used to coordinate design and manufacturing during the design stage. The chip design is itself a whole set of shared objects: high level design, schematic, netlist, verification plan, verification vectors, and simulation results both pre- and post-layout.

Figures 4 and 5 show the prototype manufacture and system integration stages of the process.

The coordination ensemble for each of the four phases forms a base layer which supports a complex set of interdependent activities. Consider Figure 3, the coordination ensemble for the chip design stage. The design team uses the chip specification to develop and verify in sequence a high level design, a schematic representation and a netlist representation of the chip design. Predesigned cells developed and maintained in a library by a cell library group are used in this sequence. The netlist is used by the layout specialist who in turn develops a physical layout representation usable by manufacturing for producing chips. This layout is simulated and verified by the design group using a verification plan and verification vectors. The design team also produces test vectors for manufacturing which can be used to test the chip samples at the next stage. Although there are many logical precedence relationships within this design process, there is no set sequence of activities because of the inherent uncertainty of doing design at the edge of technological capabilities. Much of it is iterative. For example, during the chip design stage it is common to revisit the high level design and schematic representations of the design based on the outcomes of subsequent design steps. Moreover, there is no single locus of activity in the coordination ensemble. Actors affect and are affected by shared objects concurrently. The project manager deals with manufacturing around schedule issues at the same time that the cell library group interacts with both process technology and manufacturing around the manufacturing specifications contained in the process file in order to evolve the cell library in a way that facilitates the work of the design team.

In a coordination ensemble, each actor and shared object has a responsibility (i.e., a rationale for their presence which amounts to a short description of their role in the model) and attributes or describing characteristics. In a design system, important attributes for an actor (either an individual or a group) are skills, and norms and values. Each shared object has internal data and a method by which that data can be changed by actors. This specification of objects is in line with object oriented analysis and design in software [35]. Links are defined by their actor/shared object endpoints and a full description of how the actor affects or is affected by the shared object. Actor/shared object links specify the power that actors have over the evolution and use of shared objects. It is useful when creating coordination ensembles to create a data dictionary specifying the responsibilities and attributes of all of the actors and shared objects and full descriptions of links in the ensemble. An example of the kind of data that this entails is provided in Figure 6 for an actor, shared object and link from the coordination ensemble for the design definition stage of custom silicon design shown in Figure 2.

Figure 6:
Examples of actor, shared object and link specifications for a data dictionary

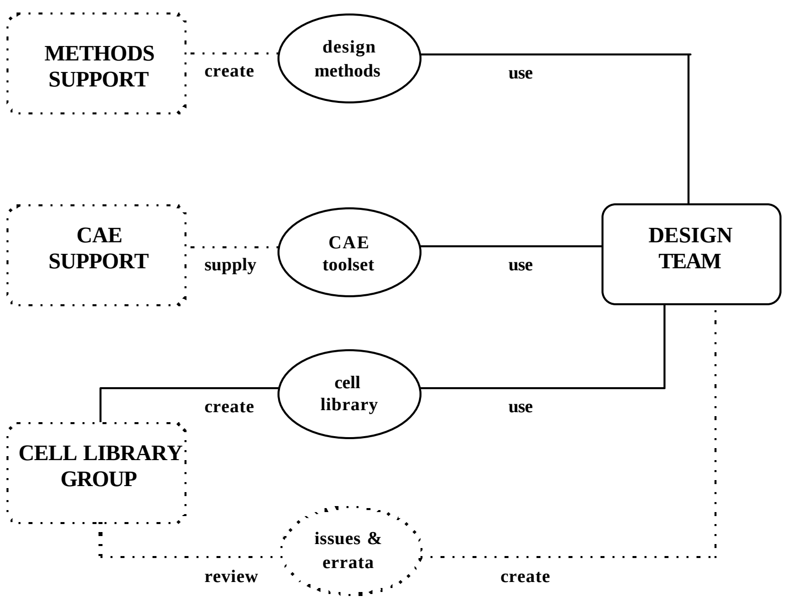


Note that the shared objects in figures 2, 3, 4, and 5 can be categorized in a number of ways. There are shared objects which are deliverables such as chip specification, layout and chip samples whose completions mark the end of the phases design specification, chip design and prototype manufacture. Thus, the proposed coordination structure approach is consistent with phase review processes [11] in which projects are marked out into distinctive non-overlapping phases with specific deliverables required for exit from one phase and entry into the next. Coordination ensembles can be used to specify the data required to manage phase review processes including detail on the people involved in a project, their responsibilities and their interdependencies.

There are shared objects which are related to managerial control such as the chip schedule and technical overview. There are also shared objects which are neither deliverables nor used for managerial control. Product architecture in Figure 2 is shared by both the system architect and the chip architect. This architecture provides rules for data management, communication protocols and signal exchange. It channels and directs the coordinated activities of both the system and chip architects but is neither a deliverable of the chip design project being modeled nor is it used for managerial control. Another category of shared object relevant to a coordinated situation which is resource constrained is the scarce resource itself, such as might happen when limited computer resources must be shared among designers in a way that creates interdependency and constrains their activities. This was not considered relevant in the modeling of custom silicon design.

Figures 2, 3, 4 and 5 represent the coordination structure of a typical custom silicon chip design project. The detail of the coordination structure of any specific design project often differs from this generic structure. Consider project C described above. In this project, the silicon designers were to function as full custom designers. This meant that if existing design methods, the CAE tool set and the cell library were not adequate for the demands of the design, these designers were to develop their own methods, take charge of updating the tool set and design their own cells. As a result, there was initially no support for design method or CAE tool set development and there was no "issues and errata" object shared by both designer and cell library group which could be used to systematically update the cell library. However, many of the designers themselves regarded their role as semi-custom designers using standard methods, tools and cell libraries. The resulting late start in identifying CAE issues, and the lack of a shared view within the project team of cell library performance, cost significant time and resources to overcome. The coordination ensemble in Figure 7 shows the coordination structure for the technical support for the designer team in the project. Those parts of the coordination ensemble which were missing early in the project are shown in gray. Management of the project is of the opinion that had there been a coordination ensemble view of the project to prompt questions concerning the adequacy of the coordination structure initially, these coordination structure deficiencies would have been corrected before they lead to serious problems. It was very hard to sort out issues like this using activity descriptions because of the complexity involved.

Figure 7:
Technical support for the design team
in Project C

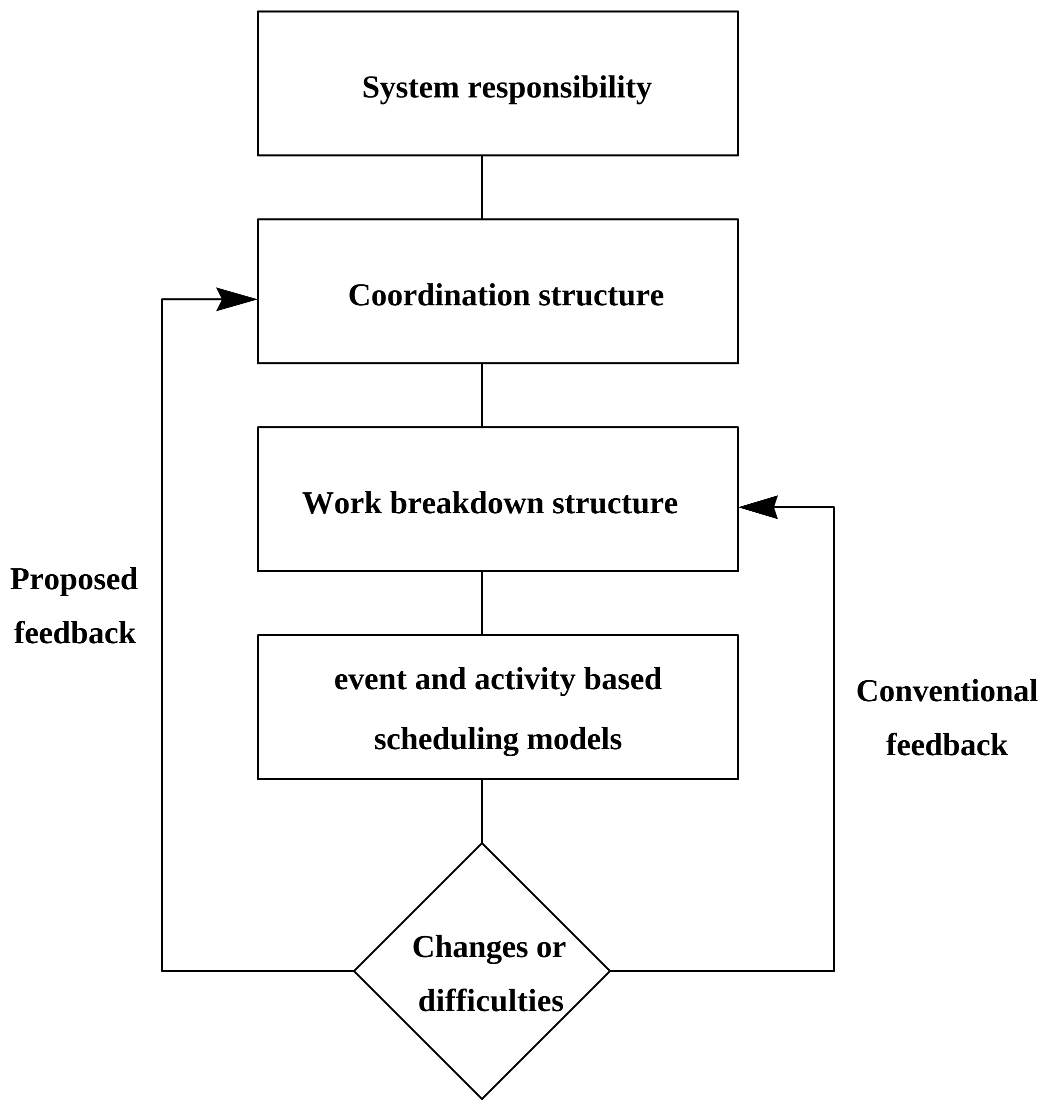


VI. SUMMARY AND CONCLUSIONS

In this paper we have introduced a method to capture and make visible the system level coordination structure of a complex situation such as that found during custom silicon design.

We argue that coordination ensembles, object based models of coordination structure, are a useful tool in the management of complex design projects. Because of their simplicity and stability, coordination ensembles form a useful front-end for conventional activity based project management. Coordination ensemble models can provide the missing system level perspective and facilitate the development of a shared view of the assignment of responsibilities and their interrelationships. They can be used in the initial work breakdown structure and task allocation, and for subsequent adjustments during a project. The place of coordination structure in the management of projects is shown in Figure 8.

Figure 8:
The role of coordination structure models
in the management of projects



Individuals and groups involved in a project can use a coordination ensemble to establish a shared view of the project. This is because of two properties of coordination ensembles. First, coordination ensembles are stable over time. An ex-post examination of the coordination ensembles of Projects A, B and C revealed that they were much more stable than the corresponding work breakdown structures.

The coordination ensembles changed very predictably at the three previously identified key points: the completion of the design specification which marks the start of chip design, the completion of the layout which marks the start of prototype manufacture, and the availability of samples which marks the start of system integration. This was not true of the work breakdown structures which changed irregularly from week to week.

Second, coordination ensembles are easily made visible. Meaningful coordination ensembles can be drawn on a single sheet of paper and made visible to all concerned, even in complex projects. This sort of visibility is important in complex projects [47].

For design projects, coordination ensembles integrate design, design process, and supporting design organization in one integrated diagram. This system level view facilitates coordinated adjustments to changes in such factors as design technology, manufacturing capabilities, design methods, design tools and design requirements. As well, when new people are introduced into a project, their roles and responsibilities in relation to others on the project can be easily explained using coordination ensembles.

Coordination ensembles are reusable. This is because they are very similar from project to project. The identification of the problems inherent in running complex silicon design projects using conventional activity based models such as CPM and Gantt charts together with the stable and visible properties of coordination ensembles lead the firm described in section III to recently begin a very large silicon design project using coordination ensembles as a basic management tool. It was a matter of 20 minutes or so for a manager using the generic coordination ensembles detailed in figures 2, 3, 4, and 5 to develop coordination ensembles for the new project. There was no corresponding level of reusability of work breakdown structures from former projects. The firm recognizes that the stability and reusability of coordination ensembles provides a basis for organizational learning between projects.

Coordination ensembles also facilitate the analysis and design of interfaces between the individuals and groups involved in a project. As mentioned above, research shows that effective cross-functional coordination differentiates successful from unsuccessful projects.

A coordination ensemble facilitates the identification and allocation of activities by bringing actors together in time and space in a simple and meaningful way. Consider the interface in Figure 2 between the chip architect and the system architect around the chip specification. The chip architect creates the chip specification; the system architect contributes to and reviews the chip specification. This arrangement means that the chip architect is the person who actually figures out what the chip specification should be. He or she does so with help from the system architect. The relationship is not a partnership. The chip architect is responsible for the chip specification. The system architect helps, and reviews the result to check the interfaces with the system as a whole, but is not responsible for creation. This interrelationship implies a whole complex set of activities and their allocation to the two actors. Using Figure 2, the interrelationship between the two actors can be changed easily, for example, to a partnership where they are jointly responsible for creating the chip specification together. This is trivial to do on the coordination ensemble, but it implies a whole different set of activity allocations than before. This means that in practice such an interface is difficult to analyze and design using a work breakdown structure.

A number of avenues for future research suggest themselves. One is the automation of the modeling process itself. This would make coordination ensembles even easier to use and work with. Efforts are currently underway to adapt industrial strength programs for the graphical representation of system designs, for use in developing coordination ensemble diagrams on a personal computer. Automation will also allow the development of features that would make coordination ensembles more useful to the design project manager. For example, it would be possible to incorporate hierarchy into the diagrams such that a user could click on a feature such as a link and be presented with useful data on the link, or on an actor and be shown the internal coordination structure of the actor. As mentioned in the paper, projects are now underway using coordination ensembles as a basic tool. Data from these projects are being gathered to better understand how coordination ensembles change over time and to measure their effectiveness as a coordination tool. Research is also underway to study what group processes are best to use with coordination ensembles for developing shared views of the coordination structure of a design project.

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