Managing an Internationally Distributed Instrumentation and Controls Project

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ABSTRACT

The Gemini 8-m Telescopes Project is faced with the challenges of demanding scientific requirements, fixed budgets, and aggressive schedules. In addition Gemini is an international project and the majority of the work itself is being done by groups within the partner countries. Gemini presents a unique managerial challenge in that not only the detailed design and fabrication of the mechanical subassemblies will be contracted out to the international community but also the software, control systems and instrumentation.

In order to meet requirements on budget and on schedule Gemini has had to develop a model for how to do distributed design, manage a distributed effort and adopt a development methodology tailored to its specific circumstances.

This paper will detail the engineering practices put in place to ensure quality, the software and hardware standards adopted, and the management techniques and tools use to promote success. In addition this paper will describe some of the lessons learned and, most importantly, what the author would change if this were repeated.

Keywords: telescopes, management model, development methodology, distributed management, software project, instruments, control systems

1. INTRODUCTION

The Gemini Project is an international partnership to build two 8-meter telescopes, one on Mauna Kea, Hawaii, and one on Cerro Pachon, Chile . The telescopes and auxiliary instrumentation will be international facilities open to the scientific communities of the member countries

The international partnership is made up of the United States, the United Kingdom, Canada, Chile, Argentina, and Brazil. The telescopes will be high performance, 8-meter aperture optical/infrared telescopes and have a planned completion date of 1998-2000.

2. CHALLENGES

2.1 Scientific Requirements

The goal of the telescopes is to exploit the best natural observing conditions and to undertake a broad range of astronomical research programs within the national communities of the partner countries. In order to reach this goal Gemini has set demanding requirements in terms of image quality, tracking, pointing, and availability (Table: 1)

Table: 1

Specification	**Requirement**	**Description**
Image Quality	0.1 arcsec	increase in 50% encircled energy diameter
Tracking	0.044 arcsec	rms jitter in line of sight
Pointing	3.0 arcsec	in service pointing
Availability	98%	time collecting science photons

In addition Gemini has requirements to support a number of different observing modes.

- Classical Observing - user manually sequences the different telescope subsystems to acquire data
- Preplanned Observing - user plans detailed use of facility in advance and submits this to facility

The Gemini 8-m Telescopes Project is managed by the Association of Universities for Research in Astronomy, for the National Science Foundation, under an international partnership agreement.

- Queue Scheduling - parts of one observer's program are interspersed with those of others in order to make more efficient use of facility
- Flexible Scheduling - programs to be executed are selected depending on environmental conditions in order to make efficient use of existing conditions
- Service Observing - program is executed by a member of observatory staff - not the Principal Investigator

These different modes create a requirement for a programmable upper layer to the software - which Gemini calls the Observatory Control System. This system acts to synchronize and sequence the actions of the different subsystems which make up the observatory system.

Also, Gemini's instruments must meet the following requirements:

- fully exploit 8-m aperture and excellent image quality of the Gemini telescopes.
- easy to use "facility class" instruments enabling a high degree of productivity from observers.
- stable throughout at least a one hour integration: < 0.1 pixel shift
- reliable and easy to maintain < 2% downtime
- performance requirements are subject to modification as the instrument definition process continues.

These demanding instrumentation requirements force one to adopt a more rigorous analysis and design phase in order to avoid the budget and schedule impact of redoing parts of the instrument during commissioning.

2.2 Aggressive Schedule

The Software project started in 1992 and has the following major milestones:

- Sep'93 - Critical Design Review of Software System Design
- Mar'95 - Conceptual Design Review of Near IR Imager
- Jan'98 - First Released Version of Software
- Apr'98 - Acceptance of Mauna Kea Software System
- Nov'98 - Deliver Near IR Imager for Commissioning
- Dec'98 - First Light; Mauna Kea
- Dec'99 - Deliver Near IR Spectrograph
- Jun'00 - Deliver Mid IR Imager
- Jun'00 - First Light; Cerro Pachon

One of the major differences between a new telescope project and adding a subsystem to an existing telescope is that everything is being done in parallel. This means that, quite often, it is only the interfaces which can be defined, the systems on either side of the interface do not yet exist.

2.3 Fixed Budget

Gemini is a fixed price project - both of the telescope systems must be delivered within a price envelope of $176 million, including inflation. This means that the specification, the schedule, and the budget are all tightly interlinked and constrained. What this means in practice is that schedule is just as important as budget.

As Gemini must pay for labor and capital expenses from the same pool of funds it makes good financial sense to purchase commercial products as they are, in general, quite inexpensive compared to the effort required to duplicate them and, especially, this reduces the amount of internal staff effort required to maintain the product. It also means that it can cost more to be late than it does to hire more staff and be early - especially when inflation and currency exchange fluctuations are taken in to account.

2.4 International Collaboration

The Gemini system is being produced as a combination of internationally bid contracts and nationally allocated work packages. The internationally bid contracts are fixed price and done by a request for proposal process while, in general, the allocated work packages represent work in which the partners possess intellectual interest and existing skills. The partner countries project offices are responsible for the process of selecting groups to do the work - generally through either national competition or allocation. The collaborative aspect of the project requires work to be distributed internationally. In order to successfully integrate the distributed parts into a coherent whole requires centralization of planning, management, budget, schedule and systems engineering.

3. WHY DO THIS

A valid question is, "Why not just form a central project team and do everything in a conventional fashion at a single site?". At first glance this would seem to be the sensible way to proceed and follows conventional wisdom.

However scientific instruments have been traditionally built by institutions with an established record in that field. Given the diversity of scientific instrumentation it is unlikely and probably intellectually undesirable to concentrate scientific instrumentation at a particular site.

Just as the telescopes are designed to exploit the best that the sites can offer the project structure is designed to exploit the best skills that the individual partners can bring to bear on the challenges represented by Gemini. The Gemini community has a number of individuals and groups with unique skills, expertise, and experience. The project benefits immensely from being able to tap these resources - indeed, access to these resources is required in order to build a telescope which satisfies the specifications, budget, and schedule requirements of Gemini.

The Gemini Construction Team will be located in Tucson from 1992-1997, move to Hawaii for the period 1998-2000, and then move on to Chile for 1999-2001. As Gemini is a fixed length project there are no construction project positions past the year 2001. It would thus be extremely difficult to convince a large number of these highly skilled individuals in the partner countries to give up their current positions to move to the Gemini Project. Indeed, it may be better for the long term health of the community if these people remain with their home institutions.

The Gemini solution to this in the area of instruments, software and controls has been to form a distributed group. In order to make this successful it was necessary for Gemini to evolve a management and development methodology model for how to do this.

4. ORGANIZATIONS INVOLVED

The six partners countries are represented by their national science agencies through national Gemini project offices. Each of the national science agencies have an operating agreement with AURA. The national project offices generally include a national project manager and a national project scientist. It is through these offices that the scientific and programmatic interfaces are maintained between the international Gemini project and the national scientific, institutional and commercial communities. This considerably decreases the number of interfaces which the international Gemini project must maintain and allows each national community to set their own objectives.

5. WORK PACKAGES / CONTRACTS

The Instrumentation and Controls area is currently divided into 5 programs:

- Infrared Program - consisting of near IR arrays, near IR array controllers, near IR imager, near IR spectrograph, mid IR arrays, mid IR imager, shared IR instruments
- Optical Program - consisting of CCDs, CCD controllers, multi-object spectrograph, high resolution optical spectrograph
- Facility Program - consisting of cassegrain assembly, instrument services and infrastructure, acquisition and guide unit (which includes on instrument wave front sensors), facility calibration unit and adaptive optics
- Principal Systems Program - consisting of observatory control system, telescope control system, instrument control systems, data handling system, interlock system
- Real Time Program - consisting of mount control system, M1 control system, M2 control system and enclosure control system

Each of the projects within a program is governed by either a Work Package agreement or a contract.

6. MANAGEMENT METHODOLOGY

The management methodology is based on a formal separation and delegation of authority and responsibility between a manager/engineer and a scientist. These two act as peers in the following manner:

- the manager/engineer is responsible for and has authority over budget, schedule and technical decisions - however he/she cannot make decisions affecting scientific performance without the agreement of the scientist
- the scientist is responsible for and has authority over scientific performance - however the scientist cannot make a decision affecting budget or schedule without the agreement of the manager/engineer
- disputes between the manager/engineer and the scientist are resolved at the next level up in the hierarchy

In practice this means that the manager/engineer and scientist must closely collaborate on the majority of the important decisions. It also promotes a level of tension which results in budget, schedule, and scientific performance all receiving adequate attention. In the Gemini system there are the following levels:

- project director
- project manager and project scientist
- instrument manager and instrument scientist
- work package manager and work package scientist

In order to make this a workable system there must be effective delegation of responsibility and authority between each level. In addition, there must be formal accountability of decisions through monthly reports / meetings and Milestone reviews.

6.1 Work Package Delegation

The project manager and project scientist delegate responsibility and authority to the instrument manager and instrument scientist through:

- the project schedule,
- project budget,
- project plan,
- project science requirements.

These documents act as the basis for five documents produced by the instrument manager/scientist and work package manager/scientist:

- error budget,
- work scope,
- management plan,
- operational concept,
- functional requirements

It is these five documents which act as definition of the limits of the delegated responsibility and authority from the instrument manager and instrument scientist to the work package manager and work package scientist.

6.1.1 Project Science Requirements

- contains top level science requirements developed by Project Scientist
- approved by the Gemini Board.
- Gemini Science Committee resolutions are incorporated as amendments
- signed off by Project Scientist

6.1.2 Error Budget

The global error budget is specified in total and broken down between the 3 subsystems:

- Instrument
- Adaptive Optics System
- Telescope

and the WP Manager has delegated authority to make trades within appropriate error budget

6.1.3 Work Scope

It is necessary to have an agreement in place about what work needs to be done, how that work will be done and reviewed, and how much effort and money is to be used to perform the work. In Gemini's system all of the partners have agreements in place which cover most of the boiler plate of a more traditional contract. The details of each Work Package are contained in a Work Scope developed by the staff responsible for performing the work.

The management of a work package is via a matrix management approach. The individual at the site who is responsible for the work remains an employee of his/her existing organization and reports to and takes direction from his/her normal supervisor. However, in all areas to do with the work package, the individual is responsible to the Gemini Controls manager. This means in practice that no changes to the work package which affect specification, budget, or schedule can be taken without prior agreement of Gemini .

6.1.4 Management Plan

This plan details the plan within which the WP Manager has delegated authority to make budget, schedule and technical decisions and consists of:

- Work Breakdown Structure
- Schedule
- Labor Requirements
- Personnel and organization chart
- Project Budget

6.1.5 Operational Concept

This document represents the expectations of the Science Community for this instrument and uses the key science cases for the instrument to justify the Science Requirements and demonstrate its expected use. It also uses key scenarios to illustrate

- the use of the instrument to perform the key science cases
- the requirements this instrument will place on the rest of the system

6.1.6 Functional Requirements

This document translates the Science Requirements and Operational Concept into the required behavior of the instrument and is used by the engineers building instrument. It is also used to decide if something which Gemini is requesting is just technical direction, and so no cost adjustment is required, or whether it is a change order, and so requires an equitable adjustment. It is also used to determine if the instrument meets its requirements - any discrepancy with this document would require rework at no additional cost to Gemini.

6.2 Work Package Accountability

The Work Package Manager is responsible for demonstrating to the Instrument Manager on a monthly basis that:

- schedule and budget goals are being met
- budget, schedule, and technical risks are acceptable
- the next Milestone review will be successful
- the Management Plan is being followed
- Standards are being met

The Work Package Manager is also responsible for demonstrating at Milestone reviews that the proposed instrument meets its requirements with acceptable risk. For a Milestone review Gemini and the National Project Office collaborate to select the review committee, which will write an advisory review report and to which the Instrument team will respond. The outcome of the review is a determination of the probability of meeting FPRD with acceptable risk and a written plan on how to proceed. As well any proposed changes to the functional requirements, operational concept, error budget, management plan are agreed to.

If the Milestone review is successful then Gemini accepts that the current design meets the current functional requirements and any future requests by Gemini to change the design as presented may incur extra costs. If the review is unsuccessful then the Work Package Manager must either request changes to the functional requirements to provide relief or direct the rework required.

7. DEVELOPMENT METHODOLOGY

7.1 Engineering Practices

Successful projects require two things:

- customers who can explain what sort of job needs doing
- engineers who can deliver a system that will do the job on time and at a price that makes doing the job worthwhile

Also, to avoid as much risk as practical it always pays to be second when buying technology,

7.2 Formal Development Process

The individual development phases and their deliverables are listed and described below.

- Work Package Development
- System Design / Conceptual Design
- Preliminary Design
- Rapid Prototyping / Critical Design
- Acceptance Testing
- Verification and Commissioning

7.2.1 Work Package Development

The output of this phase of the development consists of a Work Scope which contains the following deliverables:

- Statement of Work
- Work Breakdown Structure
- Schedule
- Cost Breakdown by WBS element
- Capital Costs
- Travel
- Key and Supporting Personnel

7.2.2 System Design / Conceptual Design

A System Design is performed for Software and Controls projects while a Conceptual Design is done for instrument projects.

7.2.2.1 System Design

The output of the System Design consists of the requirements and a conceptual design of the system.

- Package Requirements Specification.
- Environmental and Behavioral Models.
- Plans for Design Process
- Plans for Simulations / Prototypes / Trade Studies
- Documentation Plan
- Proposed Equipment

7.2.2.2 Conceptual Design

The output this phase is a conceptual design of the instrument which will meet all of the functional and performance requirements. The Conceptual Design Documentation must include all aspects of the proposed conceptual design required to determine that the conceptual design will meet the functional and performance requirements. The Conceptual Design Documentation includes:

- most recent version of Science Requirements
- updated Functional and Performance Requirements Document.
- updated Operational Concept Definition Document.
- an optical design for the instrument including such design details as optical prescription, radii, thickness and material of all components any tolerances analysis done to date
- conceptual drawings showing optical layout, mechanical packaging, and overall instrument layouts, including all applicable dimensions, material designations, and specifications.
- preliminary engineering calculations and analyses which verify that the conceptual design (including baffling and diffraction effects) meets the functional and performance requirements using optical design package.
- a detailed plan to complete remainder of the work including a schedule and a work breakdown structure
- Initial Interface Control Documents (ICDs) between various aspects of the instrument and other external systems.

7.2.3 Preliminary Design

The output of this phase for a software and controls project is a

- Preliminary Package Software Design Description
- Results of Simulations / Prototypes / Trade Studies
- Initial Work Product documents

The output for a science instrument project is:

- updated Functional and Performance Requirements Document.
- updated Operational Concept Definition Document.
- preliminary system design;
- comparison of the then current Instrument Science Requirements with the Instrument Functional and Performance Requirements Document and the Operational Concept Definition Document.
- error budgets;
- results of simulations, trades and prototypes;
- final design of the instrument optical system;
- preliminary design of the instrument mechanical layout and packaging;
- preliminary design of the Instrument Control System
- updated plans for the completion of instrument

7.2.4 Rapid Prototyping / Critical Design

We follow two different paths for science instruments and for software/controls projects.

7.2.4.1 Rapid Prototyping

For most of the software and controls packages we do not produce a formal critical design. A critical design review would review all of the software design in advance of coding - the intent being to avoid significant rework if the design does not meet the requirements. Our belief is that the only reason to do significant levels of detailed software design is if the cost of producing the software, and hence the cost of redoing the software, is significant relative to the cost of doing the detailed design. With the tools which Gemini uses for development we believe that a series of rapid prototypes is a much better investment than reviewing a formal detailed design. This consists of 4 phases; Prototype, Alpha, Beta and Final.

The Prototype phase results in a system which responds to higher level systems correctly and consists of

- Prototype Control System
- Package Software Design Description
- Update of Simulations / Prototypes / Trade Studies
- Preliminary Work Product Documents

The Alpha Control System provides the user and programmatic interfaces as seen by higher level users and systems, responds correctly to these higher level inputs and responds correctly to peer systems. A preliminary package test procedure is developed at this point.

The Beta Control System is a complete implementation of the system, has no catastrophic bugs, may contain severe bugs with or without work arounds and may also contain cosmetic bugs. A final package test procedure and a preliminary acceptance test plan is also developed at this point.

The Final Control System is the system which will be used for acceptance testing, has no catastrophic bugs, may contain severe bugs if work arounds exist and has no cosmetic bugs. The final acceptance test plan is available at this point.

7.2.4.2 Critical Design

For all science instruments and for control projects where there is significant risk and cost associated with not doing a critical design we produce the following:

- instrument performance predictions;
- a schedule for fabrication, assembly, test, and shipment of the instrument
- Final design of the Instrument Control System. This design includes a software design which includes data reduction requirements. display requirements, data storage requirements, detailed interface description interface requirements;
- drawings showing every assembly and subsystem of the instrument
- engineering calculations and analyses to demonstrate that the requirements will be met
- table of contents for the manuals;
- safety review report
- description of the packing and shipping methods to be used in delivering the instrument to the telescope site
- A means for handling the instrument when not mounted on the telescope
- Interface Control Documents specifying the interfaces between the instrument and external systems
- A copy of the preliminary design review report and the instrument team's response

7.2.5 Acceptance Testing

Acceptance testing is based on the acceptance test plan prepared by the team and approved by Gemini. This plan includes:

- a matrix of verification methods to determine compliance with the requirements and the Critical Design Documentation (e.g., by design, demonstration or test);
- description of the tests, analyses, and/or demonstrations to be performed, referenced to the verification methods matrix;
- a description of test equipment that will be utilized, referenced to the verification methods matrix;
- description of test and inspection error analysis which will be used;
- a description of any software believed to be required and a justification of the need; and
- a demonstration of reasonable reliability of both software and hardware.

The outcome of acceptance testing will be an acceptance test report which will list all the deficiencies and a plan for correcting them

7.2.6 Verification and Commissioning

For science instruments we also have a period of time on the telescope that involves the instrument team. The complete commissioning of an instrument shall consist of four phases: Instrument Commissioning, Science Commissioning, Shared Risk Use and Full Use. The intent of Instrument Commissioning is to demonstrate that the scientific performance requirements, the key science cases and key operational modes of the instrument can be accomplished. Instrument Commissioning will involve approximately 10 nights on the telescope.

The instrument team prepares a verification and commissioning plan which Gemini approves. The plan includes:

- matrix of verification methods to demonstrate that instrument functionality has not deteriorated subsequent to acceptance testing, and to continue with any further tests which can only be done on the telescope (e.g., by design, demonstration, test or observation of astronomical objects);

- a description of test equipment that will be utilize
- description of tests, analyses, astronomical observations and/or demonstrations to be performed
- description of test, inspection and astronomical observation error analysis
- initial post-delivery tests and inspections
- tests and inspections after delivery, but before mounting on the telescope, to ensure that the instruments meets the requirements
- tests of the software and control system to ensure compliance with the Observatory Control System and the Telescope Control System

7.3 Software and Hardware Standards

Gemini has adopted as many hardware and software standards as is practical (Table: 2) in order to reduce effort on infrastructure and reduce operations costs. These potential cost reductions must be balanced against the learning curves and the finite lifetime of standards.

Table: 2

Area	**Standard**
Host Workstation	Sun
Host OS	Solaris
GUI Builder	not decided
Windows	X11
Command Language	TCL
GUI	Tk
Visualization	PvWave
Host Infrastructure	CORBA / NEO
Bulk Data transfer	SDS / IMP
Observing Database	Objectstore
Archival Database	Sybase
Data Processing	IDL
Data Reduction	IRAF / ADAM
Version Control	CVS
Trouble Reporting	TkGnats
Real Time Target	68040
Real Time Target OS	VxWorks
Real Time Database	EPICS
RT Database Programming	CapFast

7.4 Review Process

There is no real point to a formal development process if there are no reviews. Each of the major phases of the development methodology have an associated review (Table 3). The goal of the reviews is not to have a large amount of presentation material and spend long periods of time listening to presenters. The current review format depends on whether it is a *real* or *virtual* review committee. The difference is that r*eal* review committees meet in person a single time with the person responsible for the work being reviewed while only a subset of a *virtual* committee ever meets in person.

The process that virtual review committees follow is:

- receive the documents ahead of time via email or ftp,
- send in comments ahead of time via email,
- reviewee prepares responses to comments
- subset of committee may/may not meet with reviewee to go over responses
- comments/responses sent via email to committee for comment
- final report issued to all concerned

Real review committees are very valuable during the early phases of a work package, especially for areas which have poorly defined requirements, difficult interfaces, or demanding functionality. *Virtual* review committees make much better use of everyone's time for areas which are well defined and reasonably non-controversial.

Table: 3	
Major Phase	**Associated Design Review**
System Design	System Design Review
Preliminary Design	Preliminary Design Review
Prototype / Critical	Prototype / Critical Design
Alpha Version	Alpha Review
Beta Version	Beta Review
Final Version	Acceptance Specification
Acceptance Testing	Acceptance Testing Review
Commissioning	Commissioning Review

8. LESSONS LEARNED

A number of lessons have been learned over the preceding three years and there will certainly be new ones. Some of the more important ones are:

1. Ownership - It is extremely important that the groups responsible for the work have a real sense of ownership of the work they are doing. This can only be developed by involving the groups in as much of the process as is possible. In the Gemini case this required starting a System Design phase with members of the partner countries involved, having members of the partner countries sit on the review committees, and having the work package responsibles develop the work breakdown structure, schedule and costing on their own.
2. Personal Contact - It is very much easier to do productive work with people whom you know well on a personal as well as professional level. It is imperative, especially during the startup of the project, to have regular face to face meetings. Gemini had someone from the controls group at the remote sites for one week per month for the initial year.
3. Delegation - You have to let go; once you involve outside groups you have to be willing to give them the freedom to make design decisions and choices. This means that the system you are building will not be done the way you would have done it. If you manage carefully enough though, it will probably be done better.
4. Moving Target - The requirements have to change. Although it would be easy to insist on having all the requirements iron clad at the start this is unrealistic. To be successful the project must meet the user's expectations, of which the requirements are only an attempt at expressing. The waterfall model of software/control development is not appropriate in this environment.
5. Communications - The key to maintaining schedule is to promote and maintain communications between the groups on either side of the interfaces. The difficulty is to balance the amount of communication against the cost in dollars and time of having this communication.

9. CONCLUSIONS

The methodology effectively meets the challenges posed by Gemini's distributed nature - it is possible to successfully manage a large, distributed development effort. However Gemini has a few more years to go before we can lay claim to ultimate success.

Distributed management is more challenging and more expensive than centralized management in the short term. However this does not necessarily translate into more difficulty and more expense for the project as a whole. Indeed, it is the author's experience that distributed management allows one to access much more qualified people to work on the project than a hiring process would result in. This is not to say that the project cannot recruit and hire highly skilled staff - just that the pool is much larger if one is willing to do it in a distributed fashion. This results in cost savings, schedule shortening, and improved system performance relative to a centralized staff - however such improvements are difficult to quantify up front.

A distributed project is the only way large science projects will be done in the future so we need to find distributed models that work and not be afraid to try new models. The advent of high bandwidth communications at reasonable rates will bring more and more of these types of group interactions into the forefront. The ability to quickly form and disperse inter-organizational project teams in a distributed fashion will be key to keeping costs and schedules in check while at the same time meeting challenging specifications with low risk solutions.

10. THINGS TO CHANGE

1. Expanded involvement earlier - The one area which the author would change significantly in a similar project would be to involve more of the partner countries principal software/controls staff in a central team for the System Design phase. The best option would be to get one or two staff from each of the institutions to spend a period of 6 months at a central site to do the system design as a coordinated team. This would have made things much easier at the point in time at which the subsystems are sent out as work packages as there would already be staff on-site with in-depth experience with the design. Although this might seem to contradict the usefulness of distributed management there is a learning curve associated with bringing the group up to sped on a design - perhaps improvements in video conferencing will remove this problem in the future.

2. Better video links and better tools for remote meetings - management by flying around is effective but very tiring and not a very good use of a managers time if it can be avoided without lessening the effectiveness.

3. Better network connectivity - it would help greatly if there were wide ranging standards, especially between the PC and UNIX worlds. The speed and cost of internet connectivity outside of North America can be quite shocking.

11. CAVEATS

The apparently rigid management structure is challenging for some teams to handle at first but to date all but the most difficult teams have found that it works in terms of keeping to budget, maintaining schedule and reaching science goals. However they have to eventually buy in to the process in order to make it work

The Astronomy community has an incredible array of resources with the experience and expertise needed to perform any of the projects required by Gemini. However only a small fraction of these resources are available and willing to work on your problems at any one point in time. In addition an even smaller fraction is willing to work to your budget and schedule.

12. ACKNOWLEDGMENTS

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