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APPENDIX A. FIELDWORK AND MACRO-ANALYSIS

This appendix provides additional detail on field research and early stages of analysis.

Interview Protocols

The following are protocols used in the customer, team member and post-session (team leader) interviews:

NPDT Customer Interview Guide

NPDT Customer: _____
Date/Time: _____
Location: _____

Pre-Interview

1. Reiterate Human Subjects protection

Affirm confidentiality
Will NOT be used to judge individual/team performance
Will NOT be shared with managers at JPL

2. Obtain consent to be audiotaped

Interview

A. Why NPDT?

What are the alternative methods/teams/processes used at JPL for conducting studies similar to the ones that NPDT does?

Why did you choose to use the NPDT team to conduct the [agency] study versus other teams and/or processes?

B. Post-NPDT

What confidence level would you put around design decisions made in the current [agency] study (or in the type of studies done by the NPDT)?

What happens to these (NPDT) studies when they're done?

How to "think about" design maturity and technology readiness level relative to NPDT-type studies?

NPDT Post-session (Team Leader) Interview Guide

ITEMS RECORDED ON SESSION TIMELINE (DURING SESSION)

1. Action Item Defined [**red**]
2. New Baseline Defined [**yellow**]
3. Trade Defined [**orange**]
4. Trade Discussion Initiated [**dark green**]

BEFORE DISPLAYING TIMELINE

OPENING QUESTION [MONIQUE RECORDS ZD'S RESPONSES AS LIST]:

How was the pace of the session?

IN PARTICULAR:

1. When was today's session 'singing'?
2. When was the session dragging?

ELABORATE-ON:

Did anything develop in the session that surprised you?
Did anything emerge that changed the course or direction of the session?
Did any breakthroughs occur that really moved the process forward? Any setbacks?
Were there any points in the session where limitation of capabilities constrained the necessary analysis and design

REVIEW SESSION SCHEMATIC TIMELINE (BEN SHOWS TIMELINE TO ZD)

1. Monique reads back list of items generated
2. Ben asks ZD to place important events on timeline

1. **Productivity of the Session - focus on transitions (referencing timeline)**

   What made productivity get better?
   What made productivity get worse?

2. **How did the session proceed as compared to the plan - Compare trades that happened in the session versus trades that were planned**

   ELABORATE ON:
   Trades that never happened
   Trades that happened in different order
Unanticipated trades that took place in the session

NPDT Team Member Interview Guide

NPDT Team Member: _____
Date/Time: _____
Location: _____

Pre-Interview

1. Reiterate Human Subjects protection

Affirm confidentiality
Will NOT be used to judge individual/team performance
Will NOT be shared with managers at JPL

2. Obtain consent to be audiotaped

Interview

A. Demographics/Organizational Information

Reporting structure
- What organization/group/subgroup do you report to?

Tenure
- At JPL (in years, months)
- On NPDT team (in years, months)

Expertise
- What specific expertise do you bring to the NPDT team?

Recruitment
- How did you get on the NPDT team?

Other Teams
- Are you a member of any other project teams besides NPDT?
  - If so, which teams?
  - On average, what percentage of your time do you spend per week on NPDT-related work?

B. Threads

1. Site Selection – ALL

The final landing site for the [agency] lander study was [coordinates]. Can you describe the rationale for settling on that particular landing site?

The location of the landing site underwent several changes over the course of the study. What things come to your mind as having triggered changes in the landing site?

What size confidence interval would you put around the location of the final landing site: [coordinates] landing site? (*Get confidence interval percentages*)

2. Reactor/Lander Configuration – ALL

Can you describe the rationale for settling on the **FINAL** reactor/lander configuration? *Can indicate we have a picture of the ONE of the reactor/lander configurations.*

The reactor/lander configuration underwent several changes over the course of the study. What things come to your mind as having triggered changes in the configuration?

What size confidence interval would you put around the final reactor/lander configuration? (*Get confidence interval percentages*)

3a. Mission Timeline – LA, KR, YH, GG, HJ, LE, RD, MW, ZD

Can you describe the rationale for settling on the use of [battery technology] versus (solar panels) for the initial deployment sequence?

What information/occurrence made it possible to close on the decision to use [battery technology] versus solar power for the initial deployment sequence?

What size confidence interval would you put around the power capacity of the [battery technology] for initial deployment sequence? (*Get confidence interval percentages*)

3b. Data Rate – UK, OV, LE, KR, HJ

Can you describe the rationale for settling on the chosen [antenna technology] for telecom?

The required telecom bandwidth changed several times over the course of the study. What factors were decisive in the choice of [antenna technology] for telecom?

What size confidence interval would you put around telecommunications bandwidth of the [antenna technology] for the cryobot mission? (*Get confidence interval percentages*)

C. Exceptions, Confidence

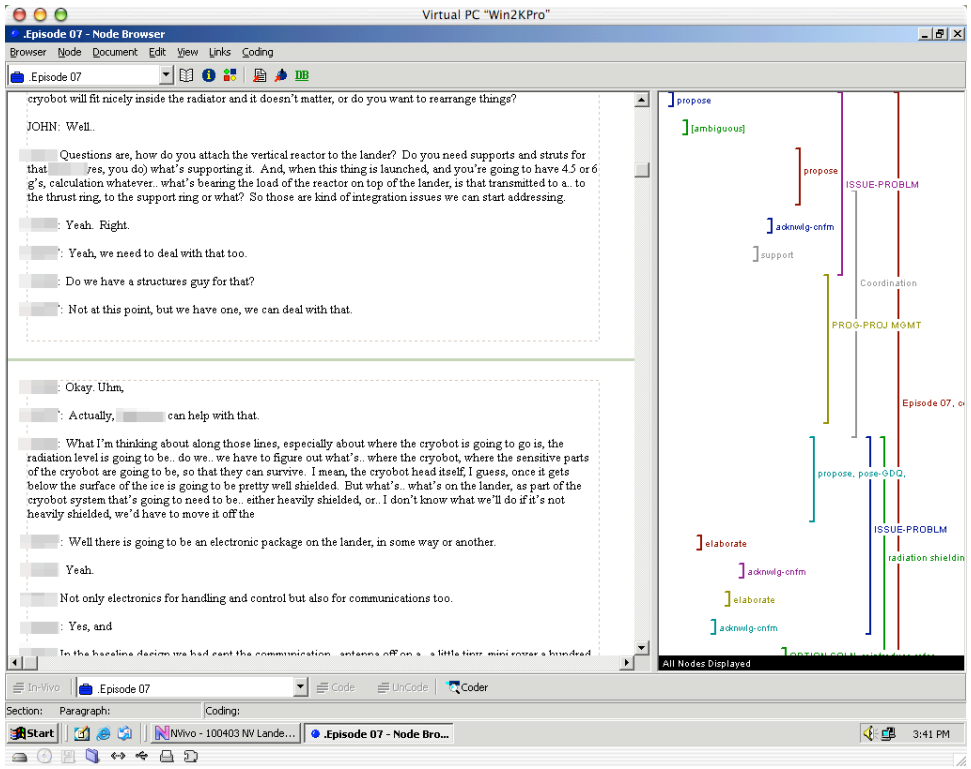
If this design were flown as is (without any substantive modifications), what would be the most worried about?

Master Timelines

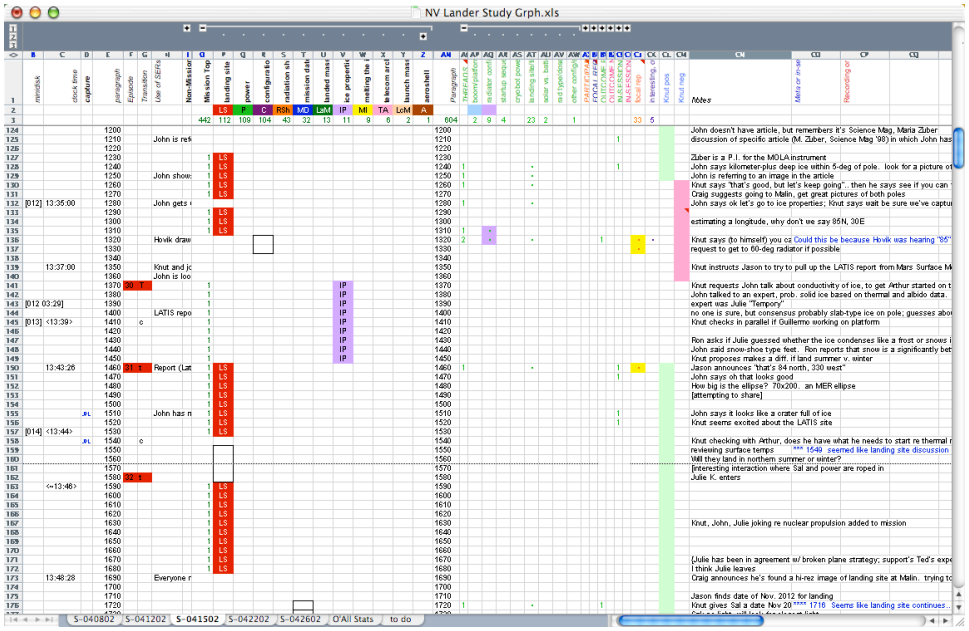
The following provides additional detail and example screens showing how a master timeline was constructed for each episode for the following purposes:

- to cross-reference between the various audio and video recordings and text transcripts coded in QSR NVivo during the one-year delay before the video record was released
- to facilitate "zooming back" to more readily discern longer term visual patterns in coding[1]
- to register initial parsing of sessions into discrete episodes on the basis (primarily) of the team leader's announced transitions
- to cross-tabulate observations from in-session notes, post-session interviews and outcome assessments pertaining to positive and negative indicators used in triangulation

[1] NVivo does not facilitate visual review of coding other than at the very fine-grained level of the actual transcript. Even this is not very satisfactory since the colour assigned to a particular code changes as one scrolls from one page of transcript to the next. Beyond that, NVivo only seems to allow for viewing the results of node searches and paragraph counts in tables.



(a) NVivo Coding Screen showing text transcript and coding bars



(b) Detail of Excel Master Timeline (each row = 10 transcr. paragraphs)

Figure A-1. Examples of NVivo Coding Screen and Excel Master Timeline

During a lengthy delay before the session video recordings were released by JPL, text transcripts were produced and imported into QSR NVivo (a) for exploratory coding with a second researcher who participated in the data collection (Monique Lambert of Stanford University). Subsequently, a master timeline for each session was created in Excel (b). These compressed the data somewhat, summarizing 10 paragraphs of transcript in a single row. This facilitated "zooming back" to see longer-term patterns in thread coding, cross-referencing between the various recordings and transcripts, and cross-tabulating positive and negative indicators from in-session notes, post-session interviews and, later, video review. Episodes were initially parsed on the basis of the team leader's announced topic transitions; indicators were summed and used as the basis for selecting certain episodes likely to be most informative when subjected to microanalysis. (A larger detail of the master timeline reproduced below with annotation.)

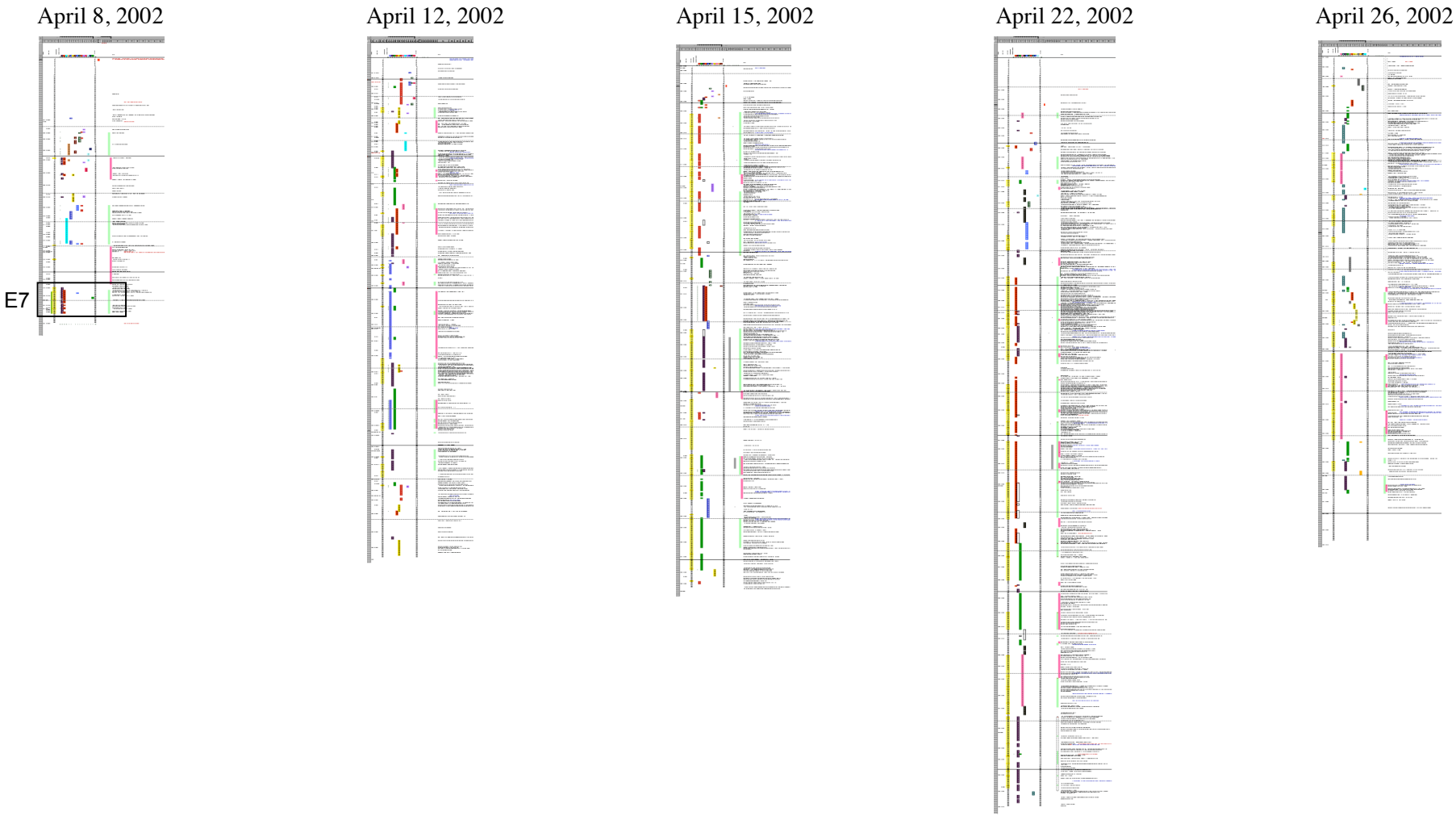


Figure A-2. Comparison of Excel Master Timelines for All Sessions
Full session master timelines show the relative length of the five sessions making up the core of the data set. Coloured bars indicate different conversational threads coded in a preliminary manner with a fellow researcher. Box indicates portion of April 8 timeline eventually parsed as Episode 7, enlarged to show detail below.

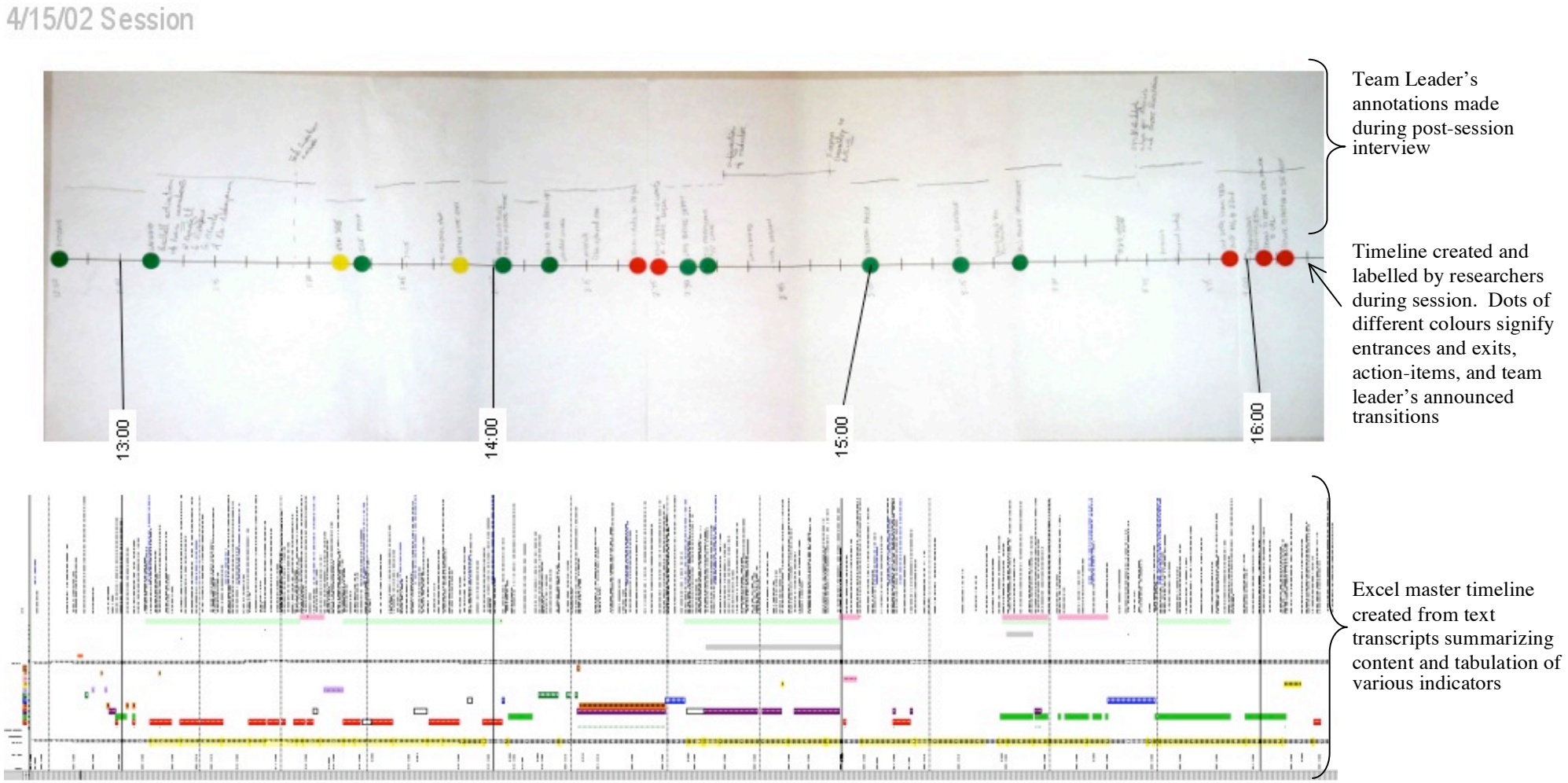


Figure A-3. Cross-Referencing In-session Timeline with Master Timeline for April 15 Session
Timelines were also created by hand during each session. These were intended to serve as prompts for the team leader during the post-session interview. Owing to time constraints in-session timelines were not used in all post-session interviews, so team leader evaluations are based primarily on transcripts of audio recordings of these interviews. However, when possible, team leader notes on in-session timelines were taken into account and cross-referenced to positive and negative evaluations

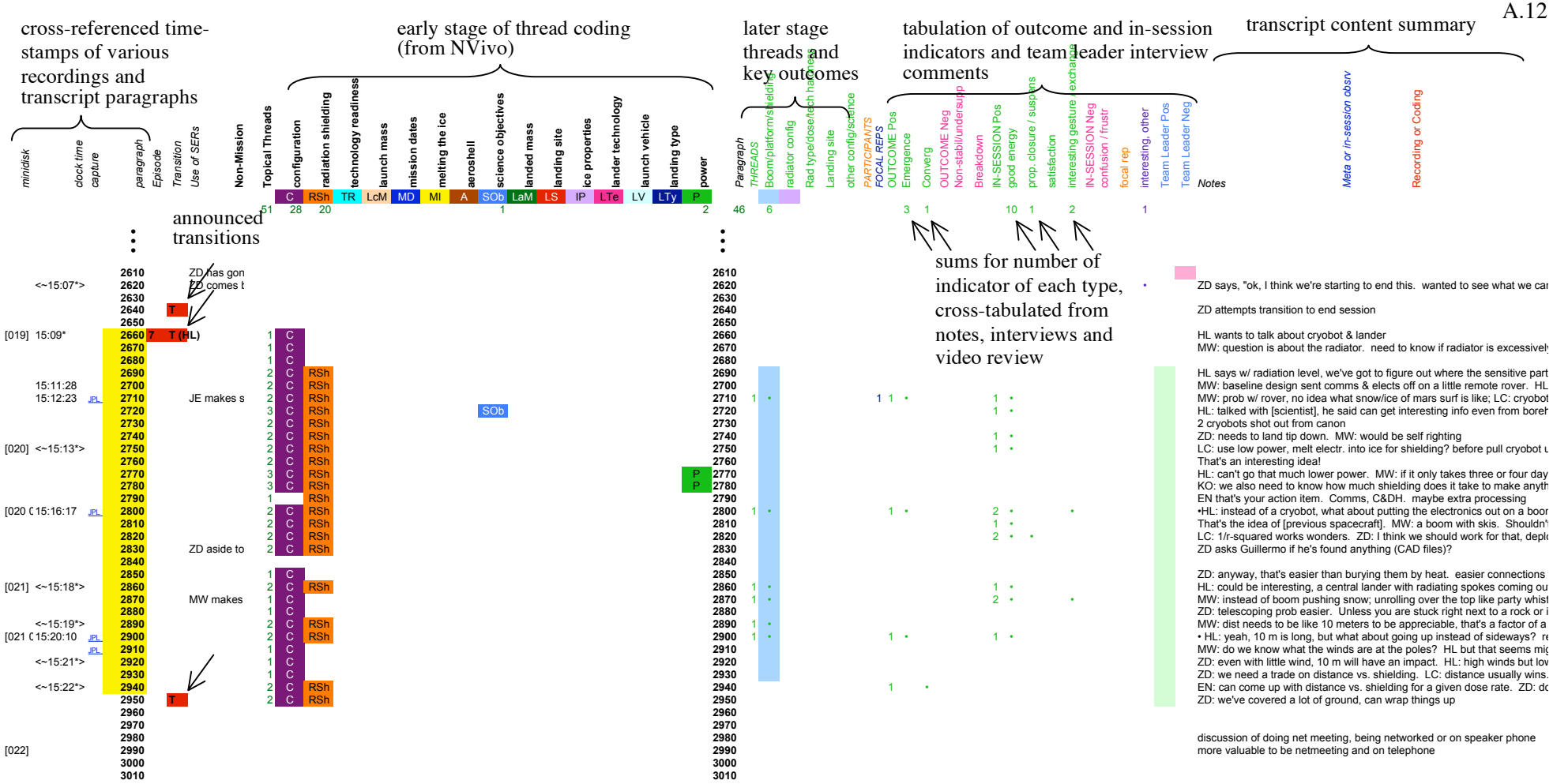


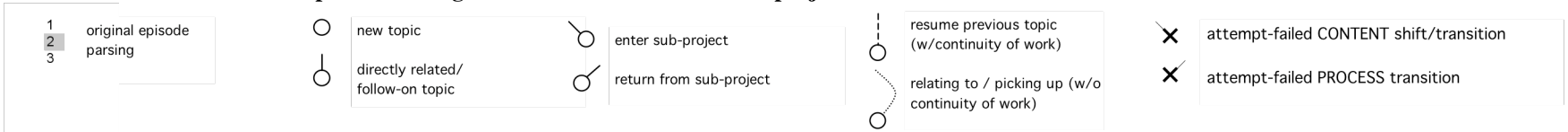
Figure A-4. Detail of Master Timeline: Episode 7

This detail shows columns in the master timeline used to cross-reference by time-stamp the various audio and video recordings; note transitions and representational activity; preliminary content coding (threads); columns for tabulating and counting outcome various and process indicators (both positive and negative) as well as team leader pos/neg evaluations. The two columns of numbers are paragraph numbers in text transcripts with each row representing ten paragraphs. A short text summary of the transcript is at the far right.

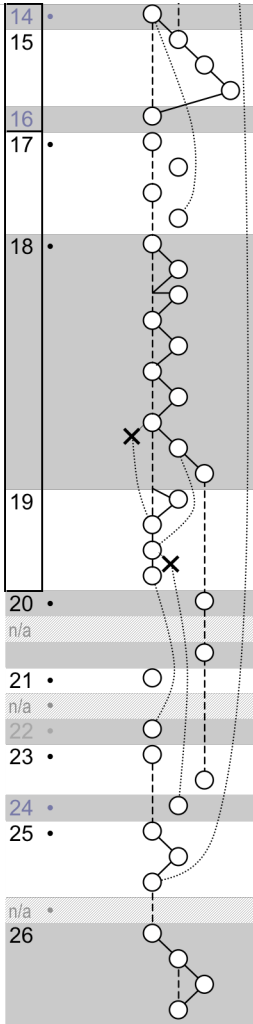
Revised Episode Parsing

Episode parsing was revisited and revised with an expanded typology of transitions and topic shifts based on conversational sub-projects (Clark, 1996). A number of episodes were found to have significant internal structure, while others were seen as resumptions of previous work that had been interrupted or suspended for various reasons. Such episodes were excluded from microanalysis for purposes of method development, as described in Chapter 4.

Table A-1. Detail of Revised Episode Parsing based on Conversational Sub-projects

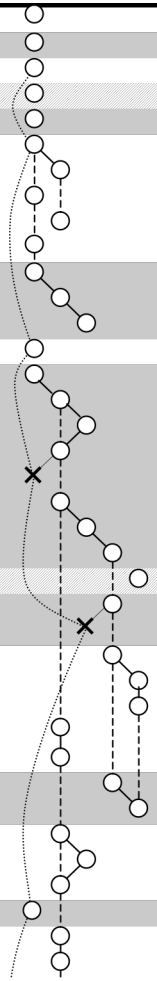


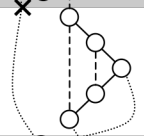
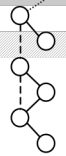
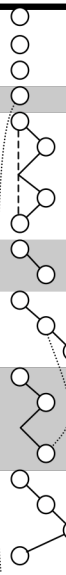
	episode	transition	topic shift	turns	initiator	prior / context	description
8 APR '02	1	•	next (actions)	293	ZD	actions, delays getting	Starts actions, ice depth, landing site, docushare, aeroshell, mass
	2	•	next (actions)	250	ZD	actions	Go to EN model
			organic			EN wants a lander in h	smart lander; reactor placement, cg
			resume			reactor placed high	EN to do calc direct energy dep. into ice, ice melting calc; MW returns, assume reactor vertical f
	3	•	next (actions)	150	ZD	actions	resend CAD file re cryobot; discuss review dates
	4	•	next (actions)	120	ZD	actions	outer surf of radiator; ice properties, insulation; thermal vs. rad energy dep. into ice
	5	•	next	460	ZD	actions concluded	suggested landing site, climate history obj.; mission dates
			organic			prev. study launch date	when will this be ready? technology readiness level; reactor testing & approval
			return				agree that 2011 is reasonable launch, w/ 2008 tech cutoff
	6		waiting	450	MW	attmpt CAD, no HJ	While waiting.. what first non-polar mission? drilling, mobility, in-situ; spectroscopy; 2322 laser d
			waiting/check-in		MW	[expert] leaves, RD ba	MW updates RD on [external expert's] comments re mobility; prog disc. [agency upper manager
	7	•	close, forced	291	HL	ZD attempt to end ses	want to talk about cryobot and lander
12 APR '02	8	•	next (actions)	320	ZD	start actions	landing site, south vs. north; discussion w/[external expert]; decision to go south
	n/a		coordination	30			three very short actions
	9	•	next (actions)	83	ZD	actions	will we melt the ice, why assume half up?; radiator sloping; docushare, return
		•	next (actions)	40	ZD	actions	getting lander info on materials, masses etc. to EN for his model
	10	•	next (actions)	141	ZD	actions	EN results of energy deposited into the ice
	11	•	next (actions	108	ZD	actions	MW reactor testing approach
	12	•	next (actions	197	ZD	actions concluded	want to work configuration; deployable radiator
	13	•	next	412	ZD		power available? tell us your needs; need melt electronics into ice?
			organic			power to melt cryobot	how long can electronics survive right next to the reactor
			resume				ZD asks KR timeline started; what power do we have available?
			waiting / parallel			sharing prob. w/power	data rates, UK to HY
			resume				power sim, max; solar panels

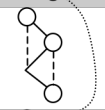
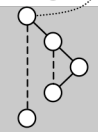


14	•	next	55	ZD		telecom architecture, though "trivial", OV re ASI & MRO; UK rad hardness of telecom electr.
15		organic/check-in	524	ZD	mention rad hardness	radiation calcs?
		organic				getting up above axial shield
		organic				rad probs w/ fiber optics; LE re data sharing copper wire; spool size, voltage
16		return	75	ZD	returning to telecom	UK, brief description after a sharing delay
17	•	next	123	ZD		power; communication protocol during descent; decide to locate agency timeline
		waiting				waiting while sharing of agency viewgraphs is sorted out; sidebar between ZD & HJ
		resume			agency timeline up	sharing delay/ collab tech. no significant design discussion
		triggered, waiting				Telecom, OV re Earth visibility, UK; 2648 false alarm re agency doc; back into waiting mode ZD
18	•	resume	1118	ZD	agency timeline finally	agency timeline; pan cam, deploy solar panels, raise mast
		organic				maybe doesn't make sense to have solar panels
		return, organic				CAD, platform diameter [stacking poss. noticed by HL] & shielding (short)
		return				KR timeline, pan photos
		organic			timeline	reactor angle, number stirlings -- this may be too fine a distiinction to count
		return				KR timeline (v. brief)
		organic			timeline	propellant, explosive chemical changes
		return				almost immediate ask power & batts raise platf, but stayed w/ timeline; LA disappears
		organic				now finally time to raise platform
		organic			platform CAD	deploy radiators, radiators view factor, conical radiator
19		resume, organic	480	ZD	LA came back in	power requirements starting reactor, motors;
		return				construct specf. time seq. w/ LA;
		directly related				KR attempting to read his back; receive power est. from HJ re platform raise (<10 paras)
		directly related				LA clarifying what he has/doesn't understand
20	•	next / resume	160	ZD		HJ to share CAD (3-ring radiator and platform)
n/a		collab tech				collab tech, why RD can't share
		resume				MW queries radiator angle; HL backshell angle 60-deg off horizontal. deployable cones when m
21	•	next	170	LE	electronics up on platfc	avionics enclosure; radiation doses and shielding
n/a	•	coordination				scheduling conversation
22	•	next / check-in	30	ZD	lull after RD leaves	Where is LA at re power
23	•	next	160	HL	ZD asked melting ice	Info no water ice on south pole
		parallel			poss HJ leaving?	background discussion, rel. inaudible. poss re radiator angle
24	•	next / close	30	ZD	ZD summarizing	KR re timeline
25	•	resume	162	HL	winding down	as a by-the-way, HL raises add'l info re landing site;
		organic				ZD says cryobot guys think melting lander into ice will be a problem; MW re SINDA
		forced / return		EN	CAD geometry	requests lander geom data in order to do runs over weekend
n/a	•	coordination			winding down	coordination, taking a week off between lander and rover sessions
26		triggered / resume	200	EN	winding down	EN received CAD jpeg, clarify; melting ice, insulation
		organic		MW	winding down	MW brainstorms radiators rolling down lander legs
		organic		EN		Does the bottom of the lander touch the ground; tanks
		return				deploying radiator; convection

15 April '02	27	•	next (actions)	310	ZD	start actions	landing site, LA & primary batt, power timeline
	28	•	next	480	ZD	actions concluded	logical to start with landing; have to go the north, must be a trade
	29		triggered	348	(ext1)	[traj. expert] enters	different orbits; 85 north w/ broken plane
			return			[traj. expert] leaves	cont LS discussion; HL gives specifics on Zuber paper
			organic				IE suggests images from Malin
			directly related				ZD requests LATIS report
	30		parallel	80	ZD	while waiting	HL tell us about ice conductivity for NC
	31		triggered	110	HY	Latis images	crater full of ice; ZD excited
	32		triggered	190	(ext2)	[traj. expert 2] enters	agreement re broken plane; est. date; Malin found, IE trying to share
			resume			[traj. expert 2] leaves	continue Landing Site. IE: Malin image found; delay in sharing
	33		parallel	60	ZD	waiting for Malin sharir	electronics deploy through cone? current angle
	34		triggered / resume	345	IE	Malin image shared	zooming in; ice depth from report; telecom and power to register change
			organic			flag 85N site to power	Anywhere north in winter, there's no light
			resume				back to locating the images on Malin, esp. for remote
	35	•	next / resume	145	ZD	have place, need time	LA, power tool, where (when) would he like to land (re solar energy)
	36	•	next	170	ZD	attempted to CAD, not	return to hear more about actions, ask HL to talk about landed mass
	37	•	next	380	ZD	next (revisiting actions	ask RL to talk about fiber optics; rad damage threshhold; hydrazine
	38	•	resume / check-in	90	ZD	check w/ LA b4 mech	LA reports from [traj. expert]; circling sun; agree to wait
	39	•	next	720	ZD	now to mech	radiator cone; unfolding petals; geometry, sizing
			organic				get radiator concept to thermal, also CAD working on it
	40	•	next	730	ZD	asks OV	OV re telecom, confirm sun & Earth low. by 3860 think they were just waiting
			waiting				ZD says "I guess we're waiting for [trajectory expert]"
	n/a		collab tech				system technician enters; collab tech
			waiting				Landing on snow, textures, "sun cups"
	n/a		coordination				HL asks RD to discuss schedule
	n/a		collab tech				MW has returned, conv. returns to collab tech, VPN
	41	•	next / resume	506	ZD	check w/mech, power	LA spreadsheet; We did that already, where numbers (breakdown); embedded CAD
			waiting			where is LE? waiting	check in with CAD; looks cool, could have gotten into art center
			resume				return to LA, asks when platform deployed
			organic				polling NC for thermal requirements (e.g. heaters)
	n/a		collab tech				MW returns, describes failure to get collab tech going
			resume				resume polling arthur for thermal; then LE re avionics and OV re telecom windows
	42		triggered	214	(ext)	[traj. expert] entry	arrival dates, running power sim, "good" in response to result; [traj. expert] leaves
	43	•	resume	340		resume with power	LA budget, LE avionics modes; NC heaters, no RHUs; length of day and night
			organic				surf temp on Mars at poles, re night & day, spacecraft heating via sun; desire to avoid using RH
	n/a		coordination	78		ZD began winding down	
	44	•	close / check-in	402	LA, ZD	ZD winding down	LA asks what about payload? propulsion, EDL? summarizing actions. Uniform site on Malin
		•	check-in				(seem to be touching base on actions); NC re melting point of ice
		•	check-in				config tasks
		•	check-in				Information on Malin site for image..

22 April '02	45 •		next (actions)	250	ZD	starting actions	ZD summarizes plan for sess; actions
	46 •		next	180	ZD, LE	concluded actions, res	Response to LE request, review sys sheet; data rate, mega-rad confusion
	47 •		next	140	ZD		after quick check-in w/ KR, asks OV to give elevation info to EN
	n/a		coordination	120			GG jumped in with a question, provoked a coordination discussion
	48 •		next	70	ZD		asks LA to say where he is; primary battery may be better solution (than solar)
	49 •		next	410	ZD		asks KR and GG detailed info on payload; embedded HL re launch vehicle
			organic				HL pipes up re landed mass, but realizes reading from the wrong table; return
			resume				GG describes cryobot tether
			resume				HL returns with correct chart
			resume				GG resumes w/ cryobot
	50		forced	400	HL	related, but forced by H	cryobot science operations, multiple bore holes;
			organic			science ops	what science on elevated platform? looking at lander CAD; catch & grab
			organic				g-loads on radiator
	51 •		check-in	80	ZD		KR working on payload
	52 •		next	1178	ZD, EN	started, then coffee bre	EN radiation dose model
			organic			EN finishes	ZD wants to change to work CAD realtime to update shielding
			organic			query to LE	LE's shielding in addition to EN's
			return			3->4m boom	boom increase to 4m and clarification of shield dimn changes
						HJ needs few more mi	first of several unsuccessful attempts to transition to KR
			waiting / resume				HL resumes clarification of shield dimension changes
			organic				would be "cool" to pump a shell full with ice melt-water for shielding
			organic			shielding spool	ZD wonders if spool will develop charge or induction; LE mentions hardening of insulations, MW
	n/a		coordination			waiting 4 MW's table s	MW mentions [agency upper mgr]'s visit
			resume				MW shares table showing radiation damage to insulations
							unable to go to KR
	53		resume / waiting	700	ZD	still waiting for KR	JFETs (still unable to go to KR, filling time); ZD polls LE on rad hardness re what MW said
			organic				telecom rad hardness; redistributing shield mass
			directly related			100krad vs. 300krad	rad exchange w/ LE re 300 krads, his shielding
			check-in				how is HJ doing adding shielding; stacking idea
			directly related			trans; held by EN	attempt go to LE, sharing delay; EN asks comfort w/ 4m boom
	54 •		resume	480	ZD, LE	fuzzy continuation	to LE shielding sheet; instability over rad
			forced / return		EN		EN forces/holds to verify his design requirements re gammas & neutrons
	55 •		resume	411	ZD	fuzzy, but now CAD	attempt go to CAD; HL interjects and elaborates stacking; identify boxes first
			organic				batteries and radiation
			return				platform area (for shielding diameter)
	56 •		next / resume	80	ZD	finally, KR	wanted power and data rate, got descr. of pan cam
	57		check-in	160	ZD	on the way to power	was going to LA/power, but check-in, asks how shielding going; shape, reduced mass, stacking
			directly related				discovering redundant electronics

	58 •		next	430	ZD	now to power, LA	Can do with battery alone, good convergence; scenarios if reactor goes down, restart etc.
			directly related				secondary batteries; scenarios if reactor goes down
	59 •		next / resume	800	ZD	skipped KR	6060 attempt KR; 6108 ask LA help w/ batteries, then HL redirects to platform {CAD, identif red
			organic			sizes, boxes	resistance of cryobot tether; stirling output; upping voltage to 600
			organic			GG just piped up	back of the envelope data rate calc; 6701 LE describing data signal on power
			return				voltage at cryobot 600V
			return				update CAD spool and cable dimensions
	60 •		next / return	714	ZD	KR shared	collection time, data volume
			organic				ZD queries GG about size of any cryobot electronics on lander
			resume / close				Also need data rate info from Beegle's liquid sampling instrument
	61 •		forced / resume	1020	HL	LE leaving	HL want resolve top science deck; redundant electronics [stacking]; pointing, interaction over CA
	n/a		other non-mission				[non-mission] HL's son would like; viz appearance of LiH
			resume				looking at CAD
			organic			trying to read off platfo	problem with units discovered
			return				
			organic				how the mast will deploy, guy wires
26 April '02			next (actions)	586			actions
			next (actions)	263		actions concluded	running through system sheet (mass)
			next	107			system sheet (power)
	62 •		forced	369	IE	IE leading sess	IE, UK flags data rate problem; Data rate new antenna; lull, antenna
	63 •		next	550	IE	picked up after telecon	summing mass; mast & radiator structure; difficulty rolling up numbers; need to
			organic			mass for radiator, therr	raising mast; guy wires, tensile structure w/ radiator
			retrun				very brief return to mass
			organic				radiator will be a IR source visible to orbiters
			return				locate, confirm mech. design spects (e.g. mass, thickness) of dynatherm radiator
	64 •		next	257	HL		wants to talk about prez mat'ls for [agency upper mgr]; IE asks what stands out
			organic			Mars bckgd for prez im	HL talking about scaling up the MSL rover design for the rover study; joking about Marge, Home
	65 •		next	170	HL	joking subsided	HL return to more serious disc. of rover; scaling "laws"; aeroshell capacity
			organic			rover mass	selective shield reduction from top of rover; scattered dose
			organic			dose	may need to revisit idea of a smart mini-rover leading large rover
	66		triggered	360	ZD	ZD enters session in p	estimate lander mass incr.;
			organic			secondary batts mass	brief: discussion of power conversion
			return				
			organic			have all the big mass	selective removal of radial shield to reduce mass
	67 •		next	230	ZD		Has issue of ice melting been talked about?
			organic				ice melt-water or vapor in the hole?
			organic				liquid vs. dust sampling, repeated bores/ops
			return				return to spacecraft melting into ice; HL says radiator design should address issue

68	•		next organic	290	ZD HL	 show radiator articulati	launch/land loads, mech structure mass; sizing mast, cg and stability; radiator/guy wire config pictures for presentation, incl. rover;
n/a			coordination			presentation	new charge numbers (project/program)
69	•		forced / resume organic	432	UK		telecom data rate prob, reconstructing agreement w/ GG; by 3618 discuss new antenna option data collection, if GG could live in his box, KR finally gets his sink rate/frame size slide "on the a
70			triggered / resume organic	550	(CAD)	driven by CAD	putting in new antenna, agreeing to get rid of old new data rate, storage, volume, uplink
71	•		next organic parallel, waiting resume	190	ZD		what are the other holes? power and thermal voltage and current supplied to cryobot; parallel w/ power and thermal Asks NC if he's happy w/ thermal and heating numbers first three days resume cryobot top-end supply voltage
72	•		forced organic organic return resume	423	LE	follow up storage incre get the dimns looking at CAD	LE asks his sheet up, added cards to increase storage CAD, identifying avionics box to reflect changes LA/LE - temp of batteries on the platform a prob? return to capturing volume changes does increase in power req. affect LA? No, power only a concern first 3 days
	•		next / close				wrap up;

APPENDIX B. MICRO-ANALYSIS

This appendix provides a more elaborate description of the categories underlying the scheme for coding design interaction. It also contains extensive coding examples in the form of Episode 7 (in its entirety) and the portion of Episode 39 corresponding to movie/image sequence #3 which involved extensive interaction with shared representations.

Coding Scheme Categories & Descriptions

The most basic aspect of the coding scheme is the metaphor that gives meaning to diagrammatic and spatial relationships. This is discussed in Chapter 5 in connection with layouts and the basic spatial metaphor: PROXIMITY = AFFINITY.[2] That is to say, the arc strengths that give rise to numerical network distances are understood to reflect the degree to which any particular statement embodies—either explicitly or implicitly—individual, personal commitment on the part of the speaker.

In the following sections, I will introduce each class and describe the specific codes within in, with examples where appropriate. This appendix also contains lengthy excerpts of actual coding to accompany the networks discussed in detail in the dissertation. In addition to the definitions embodied in the category scheme, I developed heuristics to simplify coding judgments and maintain consistency that are discussed in Chapter 5. These include:

- in general, endeavouring to stay "close to the discourse" in terms of what participants actually said, qualified as follows:
- relying on all my experience of the setting (individual interviews, observations, background research) and prior training in engineering and physics to understand utterances as referring to "the same" thing (and to paraphrase accordingly) when participants appeared to be *acting* as though they were referring to the same thing.
- coding for un-stated but implicit references to elements of previous utterances that I felt were necessary to account for the connectedness of discourse – however limiting this "carryover" to one conversational turn.
- adopting symmetry of coding strength for various components of a contribution, as determined by the apparent primary purpose of the utterance (e.g. for a contribution primarily proposing an option, I would code symmetrically strong arcs to an associated criterion, even if this was implicit).

[2] Following the notation of Lakoff & Johnson, 1980.

Design Discourse Acts

Design discourse as a broad category is distinguished by two principal features: contributions are understood by speakers (1) in direct relation to a fictive, preferred future reality, and (2) within the context of an established problematic situation or opportunity under discussion. This excluded discussion of general physical principles or time-invariant processes that did not directly implicate elements of the design, even if they were otherwise embedded in design discourse. (Instead, these would be coded as information movement.)

To preserve the integrity of the spatial metaphor, the interpretation of alignment must be somewhat different with respect to issues/problems than for options/solutions and constraints/criteria. (This is discussed in greater detail in Chapter 5.) In the table below, these differences are specifically elaborated in some entries and not in others.

Table B-1. Design Discourse Acts

design discourse acts	*strength*	*description*	*example*
propose/reintroduce	6	• option/solution: to propose or reintroduce this as a good idea, a promising approach	"We could put all the sensitive electronics on an extensible boom."
		• issue/problem: to argue this will be an issue, an important consideration, a potential problem	"If you do that, how will you deploy your cryobot?"
		• constraint/criterion: to present this as a governing constraint or a favourable aspect/ quantity to be maximized in the outcome	"That will give you a lot more surface area than the other approach."
elaborate	6	• to introduce additional information, contribute greater detail or otherwise enhance the specificity of a proposal	"Once it starts melting it will naturally tend to orient itself downward."
align	6	• a statement that this is *what we should do* (i.e. not just a good idea)	"Yeah, that is definitely the way to go." "I think we should do that."
strong support	5	• an enthusiastic statement without contributing greater detail or enhanced specificity (option=good) (issue=relevant) (criterion=important)	"I think that's a great idea." "Yeah, that's a good point, we will have to worry about that." "Yes, that will definitely be important."
support	4	• a tempered statement, qualified support	"That's an interesting idea."

design discourse acts	*strength*	*description*	*example*
neutral reference	3	• a neutral statement with regard to the design that neither aligns nor distances	"We're going to put them in the model to get a feel for how much space they're going to take."
weaken/distance	2	• option/solution: stating in a tempered manner or implying that this may not be such a good idea	"We may not want to do that because.." "I'd be worried about…if we took that approach."
		• issue/problem: this will not or will no longer present a problem or the problem will be adequately addressed	"If we do that we won't have to worry about deployment anymore."
		• constraint/criterion: this will not be as important as other concerns	"We have plenty of room to manoeuvre on cost."
call-into-question	1	• as above with regard to options, issues, or criteria, except the statement embodies more unequivocal dismissal or rejection of relevance	"We can't do that." "That is a really bad idea." "That's not relevant." "That's not even an issue in this case."

Information Movement and Management of Attention

This class of non-design discourse acts is assigned a neutral strength compared to the range established for design discourse. This is based on the observation that speakers engage in queries, clarifications and discussion of principles, processes and matters-of-fact that do not express alignment or embody a position with respect to issues, options or criteria under discussion. As discussed in Chapter 5, these arcs were assigned a shorter duration, reducing their impact on real-time network structure in a manner that seemed appropriate based on the data. (They are assigned a full duration along with other arcs in cumulative layouts.)

Table B-2. Information Movement and Management of Attention

Information/attention	*strength*	*description*	*example*
call attention	3	• alerting another participant to information that concerns them • drawing attention to a representation • requesting that a representation be displayed	"That's your action item, Dave.' "Well, what do you think about all this, Jane?" "We have a list for that, don't we?" "Can you pull up your CAD model?"

Information/attention	*strength*	*description*	*example*
ask/inquire	3	• inquiring about a feature or the numerical value of a parameter	"How big is that radiator?" "What is that thing on top there?" "What's the value of pi?"
tell/provide	3	• providing a requested parameter or explanation	"That's 20 square meters." "That's an antenna." "3.14159"
clarify/verity	3	• repetition for clarity • reiteration as a test for understanding • often concludes a repair cycle	"Ok, so you're saying…" "Right, first we'll do x then.."
repair	3	• incredulity indicating awareness or suspicion of a defect in understanding	"What?! You can't mean that." "Hang on, I don't know what you're talking about." "Why would we need to do that/worry about that?"

Meta/process Acts

Statements made, in a sense, on behalf of the group for purposes of managing process, framing issues, directions, choices, or summarizing progress. They are also used for acts requesting and making commitments to follow-up actions. These are coded directly between actors and between actors and discourse. They are of short duration, on the assumption that they are offered as "snapshots" to help the group, and that participants make their individual, personal alignments clear in separate utterances.

Table B-3. Meta/Process Acts

meta/process	*strength*	*description*	*example*
transition/close	3	• move to start or close a session or meeting • a process logic topic shift (i.e. one motivated by effective use of time or governed by an external list or agenda rather than specific content of the discussion at hand)	"I think we're all here so let's get started." "I think we've done all we can for today." "Ok, while you're doing that, let's talk about.." "Before we close, another think I'd like to discuss is.."

meta/process	*strength*	*description*	*example*
summarize (direction or choice)	6	• offering a summary of the current state of the design or a decision the group is confronted with • different from aligning because the speaker has adopted a role to some extend of speaking for the group rather than strictly for themselves	"So we'll plan on putting the electronics on the boom or mast." "Ok, so what we really need is a table of mass vs. distance for different radiation levels." "We need to find out the exact cost of these options in order to decide between them."
request to-do	6	• a direct request to specific individual(s) for specific work to be performed	"Can you run a thermal analysis and see if we will melt the ice?"
commit to-do	6	• a response committing the individual to perform a specific requested work	"George and I will work up the cost numbers for those two options."
defer	4	• a response, positively acknowledging the request, but either disregarding or deflecting certain specifics or deferring commitment on a particular completion time	"Yeah, we could do that at some point." "Uh, I don't know but I'll give it some thought/see what I can do."
decline	*	• declining to commit or rejecting a particular request	"I don't see the point of that." "I don't have the time to do that."

(*) no instances of this were observed in the data, so a specific arc strength was not determined

Semantic Network Associations

Unlike all the categories above, these arcs establish relationships directly between discourse nodes. In general, the strength values for semantic network arcs do not have a direct relationship to those for the various communicative acts described above, hence they are somewhat arbitrary. (For this reason, numerical network metrics described in the dissertation are run on actor-discourse networks only and do not take semantic relationships into account.) In real-time networks, most semantic network arcs have a normal (i.e. design discourse) duration; collaborative production arcs are assigned a long duration to highlight the clusters they form, making them more readily comparable to inscriptions in representations. It should be emphasized that for the purposes of microanalysis, semantic network relations were used for visualization purposes only, and the difficulties associated with them have not impact on the findings in this research.

Table B-4. Semantic Network Associations

semantic network	*strength*	*description*	*example*
incorporate/ co-perform	10	• links between aspects, such as a gesture or an image/schema, performed simultaneously or inextricably embodied in a contribution • often involves a gesture or image/schema in conjunction with a matter-of-fact or an option/solution • overtly imagistic language • spatial relations in prepositional phrases that are an important basis for connectedness in discourse	"It could open like this.." (gestures with arms) "It could open like an umbrella." (various distance schema describing possible relationships between the lander and the electronic package in Episode 7, sequence #1)
associate	10	• links between elements conveyed by propositional relationships in design reasoning: e.g. "implies", "causes", "will result in", "entails", "requires" • often involves elements of different discourse type, e.g. between options and criteria	"That design will give us the best heat transfer." (*)
attach quantity/ attribute	10	• links between a numerical quantity and an attribute of the same logical type: e.g. "is", "has" • an attribute followed by a number or specific value	"12 kg" to an attribute like "mass" "aluminium" to an attribute like "material"
collaborative production	20	• a direct, logical, consequential or follow-on relationship between nodes of the same type contributed by different participants • with a stand-alone or independent quality (as opposed to a constructive or additive contribution rather than as an alternative (i.e. that would implicitly or explicitly require a choice) • would be considered part of "the same" idea at a higher level of aggregation or generality	(see various collaborative productions coded in sequences from Episode 7 and Episode 39 reproduced below)

semantic network	*strength*	*description*	*example*
weaken	0	• contested relationship in the first three categories above (**) • partial withdrawal or reversal of a collaborative contribution (either by the proposer or another participant) (***)	(**)

(*) an important shortcoming exists with regard to semantic associations involving issues, as discussed in the dissertation. A more complex logic is required to allow issues to be distanced in real-time networks. For this reason, semantic associations were not coded with issues when the arcs would interfere with distancing as issues were discussed.
(**) as discussed in the main text, some method of weakening semantic network arcs was required but this approach (a zero-strength arc) takes advantage of particular behaviour of the SoNIA program and is not generally satisfactory for a number of reasons.
(***) when a collaborative contribution was completely rejected by another participant, rather than weakening the semantic arc I prematurely terminated it, thereby allowing the nodes that were the basis of sharp disagreement to drift farther apart.

Representational Acts and Inscription

Representational acts take place between human actors and representations. They operate in conjunction with design discourse or information movement, whichever is appropriate for a given contribution. Because they operate directly between actors, they are assigned a short duration in real-time networks, in order to bias network structure toward actor-discourse relationships. (They are assigned a full duration along with other arcs in cumulative layouts.)

Table B-5. Representational Acts

acts with representations	*strength*	*description*	*example*
explain/describe	3	• neutral naming or description of features already present in a representation	"There is the lander, with the power source sitting on top of it." "That column shows the mass of the various subsystems."
implicate	6	• more emphatic indication or pointing • active (often gestural) • incorporation of an aspect or feature of a representation in a contribution • animation of a representation with a gesture	"We could take this thing (points) and slice it into two halves like this." (gestures over the CAD display)

acts with representations	*strength*	*description*	*example*
create/add/change	10	• changing the physical form of a representation, e.g. by drawing • giving explicit directions and instructions for specific changes to be made to a representation by an operator	"What I'm talking about is this..(moves to whiteboard). You need a bracket here (drawing) to connect them."
notice	6	• a new topic raised by a participant with reference to something noticed in a representation, in a manner that departs, shifts or redirects the flow of the preceding conversation	"Is that thing on top (referring to the CAD model) your antenna?" (previous discussion having been unrelated to the antenna)

Inscription defines relationships between discourse and representations. Strengths are assigned to echo the strength of engagement between the human participant and the representation in the corresponding representational act. Because representations are persistent, and inscriptions are associated with discernable features or relatively robust changes, they are assigned a long duration.

Table B-6. Inscription

inscription	*strength*	*description*	*example*
inscribe 1	3	• in conjunction with explain/describe	(as above for explain/describe)
inscribe 2	6	• in conjunction with notice or implicate	(as above for notice or implicate)
inscribe 3	10	• in conjunction with create/add/change	(as above for create/add/change)

Diagrammatic Examples

Table B-7 Example Sequence of Network Diagrams with Design, Info Mgmt. & Meta/Process

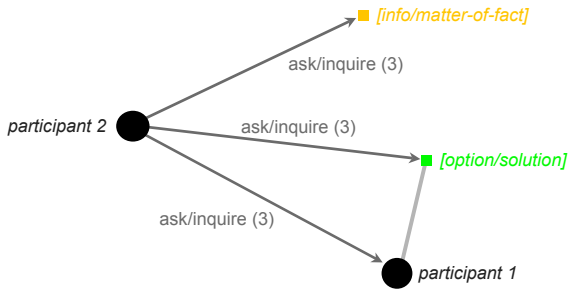
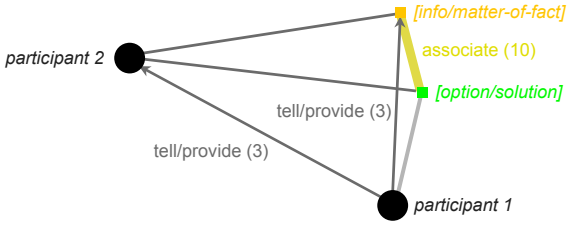
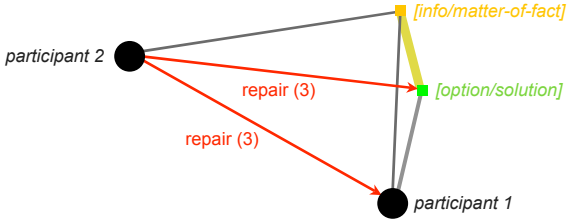
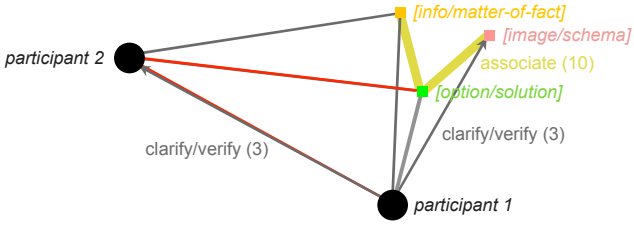
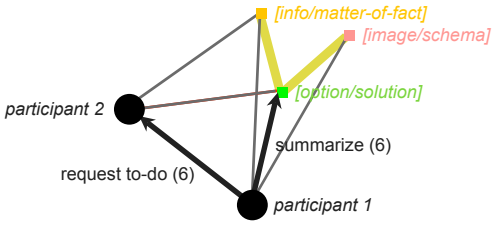
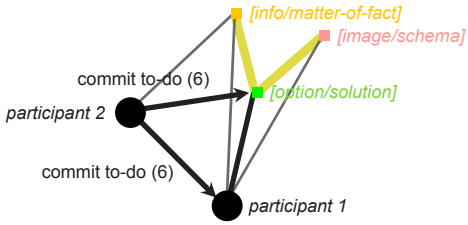
network diagram	*act description*
	Participant 2 asks a question of participant 1 about a matter of fact concerning a proposal that participant 1 has just made.
	Participant 1 answers the question, specifying the matter of fact and/or its relationship to the option/solution.
	Participant 2 does not understand the relationship described by participant 1 and requests clarification.
	Participant 1 offers a clarification in the form of an image or schema associated with the option.
	Participant 1 summarizes the option as a design direction and asks participant 2 to carry out a further action, such as an analysis.
	Participant 2 agrees to complete the requested action or analysis.

Table B-8 Example Sequence of Network Diagrams Illustrating Symmetry of Arcs to Multiple Nodes and Implicit References

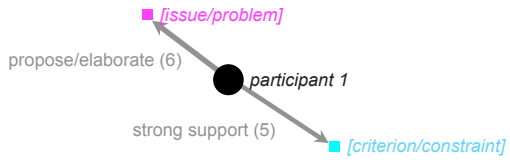
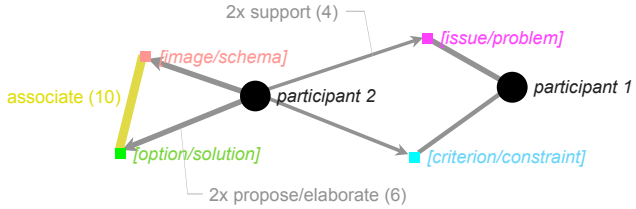
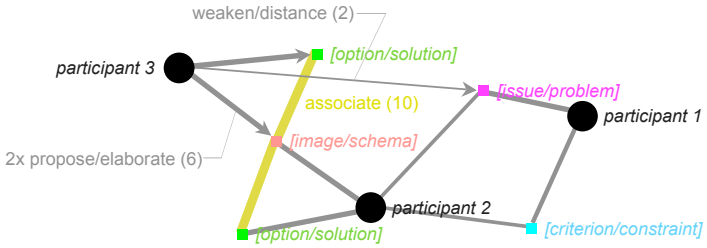
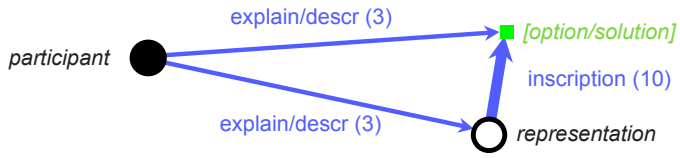
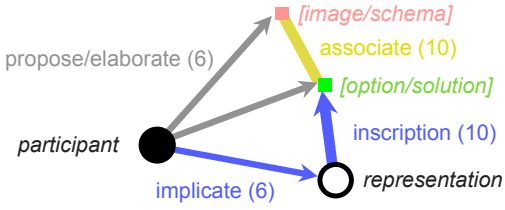
network diagram	*act description*
	A participant proposes an issue, mentioning the importance of a previously-established constraint.
	A second participant proposes an option / solution along with an image/schema. Both elements of the proposal receive the same strength. The issue and constraint are carried over as implicit referents from the previous turn.
	A third participant distances the issue explicitly and makes a second proposal embodying the same image/schema. No arc to the constraint is coded because it was not mentioned and implicit references are not carried over more than one turn.

Table B-9 Example Network Diagrams for Various Acts with Representations

network diagram	*act description*
	A participant describes a pre-existing feature of a representation that depicts an option/solution.
	A participant elaborates an option / solution depicted in a representation with a linguistic image/schema and an animating gesture.

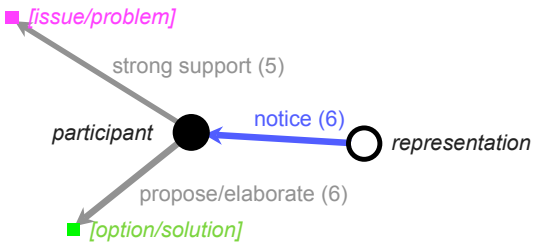
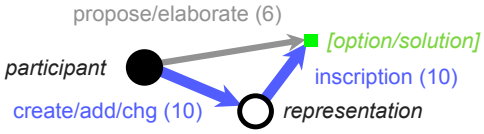
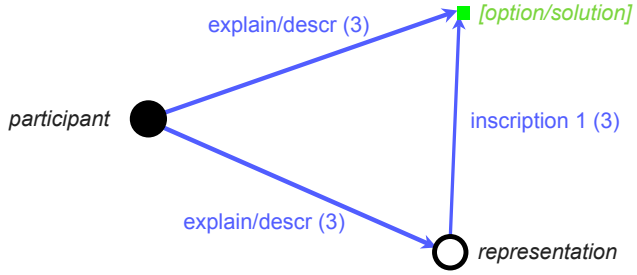
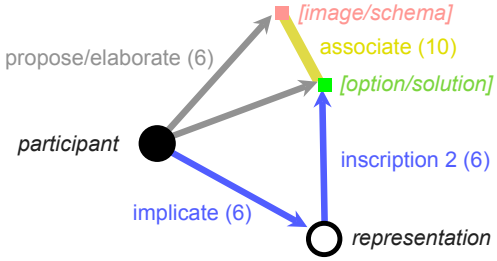
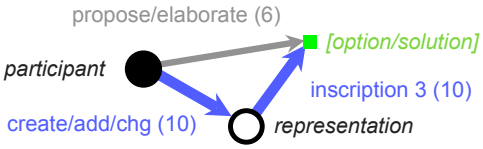
network diagram	*act description*
	A participant proposes an option to circumvent an issue on the basis of something noticed in a representation. (The option is not inscribed or depicted in the representation.)
	A participant proposes an option by drawing on a whiteboard.

Table B-10 Example Network Diagrams showing Graduated Levels of Inscription

network diagram	*act description*
	A participant describes a pre-existing feature of a representation that depicts an option/solution.
	A participant elaborates an option / solution depicted in a representation with a linguistic image/schema and an animating gesture.
	A participant proposes an option to circumvent an issue on the basis of something noticed in a representation. (The option is not inscribed or depicted in the representation.)

Coding Samples

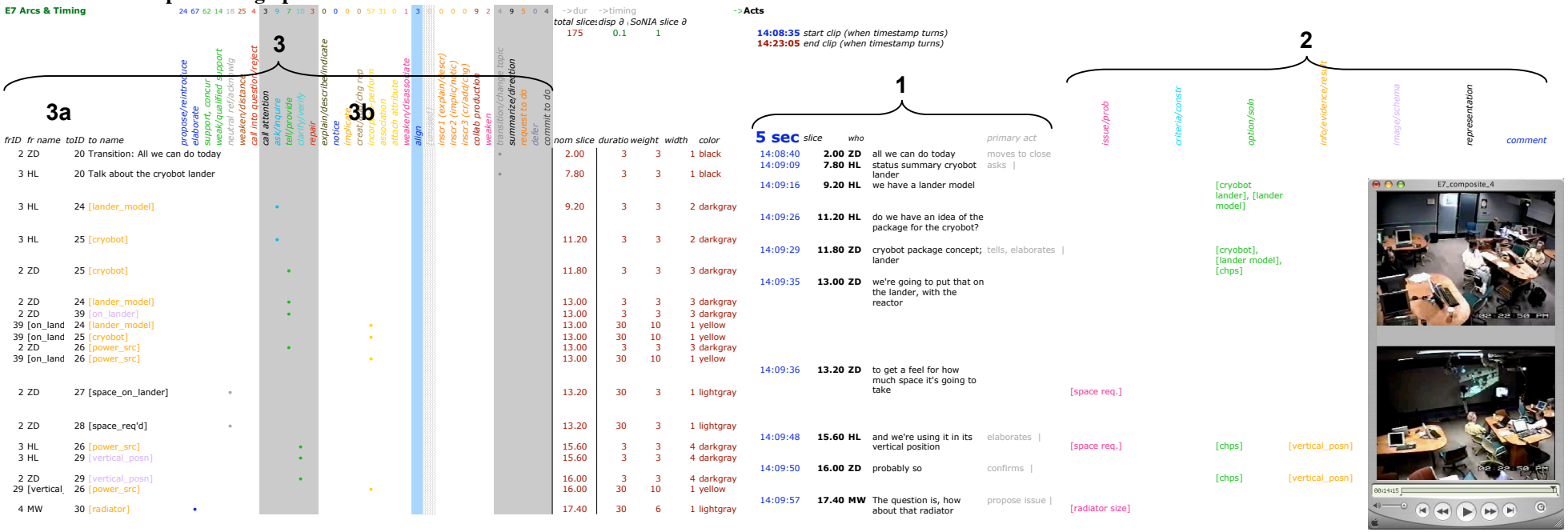
The following tables present extensive samples of the actual coding from which networks were generated for some of the interaction data described in detail in the main body of the dissertation. It is included here to make the results more transparent and to provide example coding of a range of interaction to complement the categorical descriptions presented above.

Because detailed information about the design of spacecraft is potentially export-controlled, it was necessary for JPL to review transcripts, video clips and other descriptions generated in this research prior to publication. In compliance with the terms of research access to the JPL site, and to avoid violating export control law, I complied with the JPL reviewer's requests to remove or disguise a substantial amount of information in several episodes I had selected and subjected to microanalysis. No information was redacted from Episode 7, leaving it the most intact and providing readers the most ready access to the original data.

Episode 7 did not involve the use of any persistent, shared external representations of the type with which I am centrally concerned, so it does not contain coding for representational acts. For this reason I have reproduced additional coding from Episode 39 (interaction corresponding to the beginning of movie/image sequence #3) which had extensive and dynamic use of shared representations.

The first table and its description below give an overview of the way the actual coding spreadsheets were used. The following tables reproduce coding from Episodes 7 and 39, respectively.

Table B-11 Example Coding Spreadsheet Detail



This is an example of the spreadsheet used to facilitate coding. The process was done in three stages, labelled above. All three were performed with simultaneous review of a clip of the source video (two camera angles in one frame) of the episode being coded. **(1)** First, a pass was made to identify relatively distinct design moves (cf. Goldschmidt 1998, 1995, 1992) within the interaction, who was principally involved, the apparent purpose of the move, and to record the video time stamp. (The spreadsheet automatically calculates a slice number based on 5-second interval.) **(2)** Then a second pass was made to create a provisional list of possible nodes, categorized by type. This provisional list was reviewed and a node definition table was generated (not shown). It was at this point that the first decisions were made about what discourse elements would become nodes, when nodes would be renamed and/or new nodes would be created as the conversation evolved. Once the node definition table was complete, a third pass **(3)** was made to define the actual arcs that would make up the network. This involved deciding how many arcs each move would give rise to and specifying the start and end nodes (3a), and categorizing each specific act by placing a bullet in the appropriate column corresponding to the act typology (3b). Once these decisions were made, look-up tables were used to automatically fill in a great deal of additional information required by the SoNIA program, such as the actual node labels, precise arc timing, colour information and overall timing for node appearance and disappearance.

Table B-12 Episode 7: Coding Sample

E7 Arcs & Timing

E7

frID	fr name	toID	to name	issue/prob	criteria/constr	option/soln	info/evidence/result	image/schema	representation	propose/reintroduce	elaborate	support, concur	weak/qualified support	neutral ref/acknowlg	weaken/distance	call into question/reject	call attention	ask/inquire	tell/provide	clarify/verify	repair	explain/describe/indicate	notice	implicate	creat/add/chg rep	incorp/co-perform	association	attach attribute	weaken/disassociate	align	transition	inscr1 (explain/descr)	inscr2 (implic/notic)	inscr3 (cr/add/chg)	collab production	weaken	transition/change topic	summarize/direction	request to do	defer	commit to do	nom slice	duratio	weight	width	color
				24	67	62	14	18	25	4	3	9	7	10	3	0	0	0	0	57	31	0	1	3		0	0	0	9	2	4	9	5	0	4	->dur	->timing							
																																								total slices	disp ∂	SoNIA slice ∂						
																																								175	0.1	1						
2	ZD	20	Transition: All we can do today																																	•					2.00	3	3	1	black
3	HL	20	Talk about the cryobot lander																																	•					7.80	3	3	1	black
3	HL	24	[lander_model]			•												•																							9.20	3	3	2	darkgray
3	HL	25	[cryobot]			•												•																							11.20	3	3	2	darkgray
2	ZD	25	[cryobot]			•													•																							11.80	3	3	3	darkgray
2	ZD	24	[lander_model]			•													•																							13.00	3	3	3	darkgray
2	ZD	39	[on_lander]				•												•																							13.00	3	3	3	darkgray
39	[on_land	24	[lander_model]			•																•																			13.00	30	10	1	yellow
39	[on_land	25	[cryobot]			•																•																			13.00	30	10	1	yellow
2	ZD	26	[power_src]			•													•																							13.00	3	3	3	darkgray
39	[on_land	26	[power_src]			•																•																			13.00	30	10	1	yellow
2	ZD	27	[space_on_lander]		•				•																																13.20	30	3	1	lightgray
2	ZD	28	[space_req'd]	•					•																																13.20	30	3	1	lightgray
3	HL	26	[power_src]			•														•																					15.60	3	3	4	darkgray
3	HL	29	[vertical_posn]				•													•																					15.60	3	3	4	darkgray
2	ZD	29	[vertical_posn]				•													•																					16.00	3	3	4	darkgray
29	[vertical	26	[power_src]			•																•																			16.00	30	10	1	yellow
4	MW	30	[radiator]			•					•																														17.40	30	6	1	lightgray
4	MW	27	[space_on_lander]		•							•																													18.40	30	5	1	lightgray
4	MW	31	[radiator_size]	•							•																														18.40	30	6	1	lightgray
4	MW	25	[cryobot]			•																•																			19.20	30	3	1	lightgray

Acts

14:08:35 *start clip (when timestamp turns)*
14:23:05 *end clip (when timestamp turns)*

5 sec *slice* *who*

14:08:40	**2.00 ZD**	all we can do today
14:09:09	**7.80 HL**	status summary cryobot lander
14:09:16	**9.20 HL**	we have a lander model
14:09:26	**11.20 HL**	do we have an idea of the package for the cryobot?
14:09:29	**11.80 ZD**	cryobot package concept; lander
14:09:35	**13.00 ZD**	we're going to put that on the lander, with the reactor
14:09:36	**13.20 ZD**	to get a feel for how much space it's going to take
14:09:48	**15.60 HL**	and we're using it in its vertical position
14:09:50	**16.00 ZD**	probably so
14:09:57	**17.40 MW**	The question is, how about that radiator
14:10:02	**18.40 MW**	need to know if it's excessively large
14:10:06	**19.20 MW**	or if the cryobot will fit inside and it doesn't matter

E7

frID	fr name	toID	issue/prob	criteria/con	option/soln	info/eviden	image/sche	representat	to name	propose/rei	elaborate	support, co	weak/qualif	neutral ref/	weaken/dis	call into qu	call attentic	ask/inquire	tell/provide	clarify/verif	repair	explain/des	notice	implicate	creat/add/c	incorp/co-p	association	attach attril	weaken/dis	align	inscr1 (exp	inscr2 (imp	inscr3 (cr/a	collab prod	weaken	transition/c	summarize/	request to	defer	commit to	nom slice	duratio	weight	width	color	5 sec	slice	who	
4	MW	25			•				[cryobot]					•																											19.20	30	3	1	lightgray	14:10:06	**19.20**	**MW**	or if the cryobot will fit inside and it doesn't matter
4	MW	32				•			[fit_inside]					•																											19.20	30	3	1	lightgray				
32	[fit_insid	25			•				[cryobot]																•															19.20	30	10	1	yellow				
32	[fit_insid	30			•				[radiator]																•															19.20	30	10	1	yellow				
																																													14:10:13	**20.60**	**MW**	also how do you attach the reactor to the lander, if you need supports & struts
4	MW	33	•						[pwr_src_struct_inte	•																															20.60	30	6	1	lightgray				
4	MW	26			•				[power_src]					•																											20.60	30	3	1	lightgray				
4	MW	35				•			[attach/support]			•																													20.60	30	5	1	lightgray				
35	[attach/s	26			•				[power_src]																•															20.60	30	10	1	yellow				
35	[attach/s	24			•				[lander_model]																•															20.60	30	10	1	yellow				
39	[on_land	26			•				[power_src]																•															20.60	30	10	1	yellow				
																																													14:10:20	**22.00**	**MW**	and when this thing is launched, what's supporting it, if you're going to have --g's
4	MW	33	•						[pwr_src_struct_integr	•																															22.00	30	6	1	lightgray				
4	MW	34		•					[launch_g's]		•																													22.00	30	6	1	lightgray				
34	[launch_	35				•			[attach/support]																		•													22.00	30	10	3	yellow				
																																													14:10:38	**25.60**	**ZD, HL**	
2	ZD	31	•						[radiator_size]			•																												25.60	30	4	1	lightgray				
2	ZD	33	•						[pwr_src_struct_integr]			•																												25.60	30	4	1	lightgray				
3	HL	31	•						[radiator_size]			•																												25.60	30	4	1	lightgray				
3	HL	33	•						[pwr_src_struct_integr]			•																												25.60	30	4	1	lightgray				
																																													14:10:41	**26.20**	**HL**	do we have a structures guy?
3	HL	2							ZD									•																					26.20	3	3	2	darkgray				
3	HL	33	•						[pwr_src_struct_integr]									•																						26.20	3	3	2	darkgray				
2	ZD	3							HL										•																				26.20	3	3	3	darkgray				
																																													14:10:50	**28.00**	**HL**	where sensitive part of cryobot sys on lander
3	HL	36	•						[where_sensitive_cry	•																															28.00	30	6	1	lightgray				
3	HL	37		•					[rad_level]		•																													28.00	30	6	1	lightgray				
3	HL	41			•				[sensitive_cryob_electr		•																															28.00	30	6	1	lightgray				
39	[on_land	41			•				[sensitive_cryob_electronics]																•															28.00	30	10	1	yellow				
3	HL	25			•				[cryobot]					•																										28.00	30	3	1	lightgray				
																																													14:11:02	**30.40**	**HL**	cryobot head shielded below the ice
3	HL	38				•			[ice_protects]					•																										30.40	30	3	1	lightgray				
25	[cryobot	38				•			[ice_protects]																•															30.40	30	10	1	yellow				
																																													14:11:12	**32.40**	**HL**	but what's on the lander, either heavily shielded, or..
3	HL	36	•						[where_sensitive_cryob	•																															32.40	30	6	1	lightgray				
3	HL	40		•					[heavily_shield]			•																												32.40	30	4	1	lightgray				
3	HL	39				•			[on_lander]			•																												32.40	30	4	1	lightgray				
41	[sensitiv	40		•					[heavily_shield]																		•													32.40	30	10	3	yellow				

Table B-13 Episode 39: Coding Sample (Sequence 3)

E39 Arcs & Timing

E39

->dur ->timing

total slices: 326 | disp ∂: 0.1 | SoNIA slice ∂: 1

frID	fr name	toID	issue/prob	criteria/constr	option/soln	info/evidence/result	image/schema	representation	to name	propose/reintroduce	elaborate	support, concur	weak/qualified support	neutral ref/acknowlg	weaken/distance	call into question/reject	call attention	ask/inquire	tell/provide	clarify/verify	repair	explain/describe/indicate	notice	implicate	creat/add/chg rep	incorp/co-perform	association	attach attribute	weaken/disassociate	align	(unused)	inscr1 (explain/descr)	inscr2 (implic/notic)	inscr3 (cr/add/chg)	collab production	weaken	transition/change topic	summarize/direction	request to do	defer	commit to do	nom slice	durati	weigh	width	color
										25	90	72	9	16	35	6	14	39	36	11	21	17	5	16	15	49	11	11	6	13		3	6	13	17	3	4	15	19	1	6					
4	MW	39	•						[melting_ice]	•																																37.40	30	6	1	lightgray
4	MW	40		•					[heat_to_ice]	•																																37.40	30	6	1	lightgray
4	MW	26			•				[cone_radiator]							•																										37.40	30	1	1	red
4	MW	28				•			[75_deg]							•																										37.40	30	1	1	red
4	MW	41					•		[horizontal]	•																																37.40	30	6	1	lightgray
3	HL	41					•		[horizontal]												•																					38.40	3	3	1	red
41	[horizont	40		•					[heat_to_ice]																		•															39.60	30	10	3	yellow
4	MW	44			•				[insul_bot_rad_up]			•																														39.60	30	5	1	lightgray
41	[horizont	44			•				[insul_bot_rad_up]																	•																39.60	30	10	1	yellow
3	HL	26			•				[cone_radiator]						•																											40.00	30	2	1	lightgray
3	HL	44			•				[insul_bot_rad_up]			•																														40.00	30	5	1	lightgray
3	HL	39	•						[melting_ice]			•																														40.00	30	5	1	lightgray
3	HL	40		•					[heat_to_ice]			•																														40.00	30	5	1	lightgray
3	HL	35	•						[fit_in_aeroshell]			•																														44.00	30	5	1	lightgray
3	HL	70		•					[aeroshell_size]			•																														44.00	30	5	1	lightgray
3	HL	24						•	<CAD_Cone_Radiator>													•																				44.00	3	3	2	blue
3	HL	32				•			[bot_rad_#m]					•																												44.00	30	3	1	lightgray
32	[bot_rad	70							[aeroshell_size]																		•															44.00	30	10	3	yellow
4	MW	35	•						[fit_in_aeroshell]					•																												46.60	30	3	1	lightgray
4	MW	42			•				[flat_panels/open_u	•																																46.60	30	6	1	lightgray
4	MW	41					•		[horizontal]	•																																46.60	30	6	1	lightgray
4	MW	43					•		[open_like_object_1	•																																46.60	30	6	1	lightgray
42	[flat_par	41					•		[horizontal]																	•																46.60	30	10	1	yellow
42	[flat_par	43					•		[open_like_object_1]																	•																46.60	30	10	1	yellow
4	MW	47					•		[manner_1_outward]		•																															47.60	30	6	1	lightgray
47	[manner	42			•				[flat_panels/open_up]																	•																47.60	30	10	1	yellow

Acts

14:33:23 *start clip (when timestamp turns)*
15:00:28 *end clip (when timestamp turns)*

5 sec

time	slice	who	
14:36:25	**37.40**	**MW**	sounds like haven't made much progress toward getting to horizontal, only added 15 degrees
14:36:30	**38.40**	**HL**	horizontal?
14:36:36	**39.60**	**MW**	we wanted horizontal so insulate bottom avoid shining onto the ice
14:36:38	**40.00**	**HL**	yeah you're right.
14:36:58	**44.00**	**HL**	This prob. best you can do w/ cone; taking up most of bottom radius
14:37:11	**46.60**	**MW**	can you have it horizontal, open up like a [familiar object]
14:37:16	**47.60**	**MW**	elaborates, [opens in manner 1]

E39

frID	fr name	toID	issue/prob	criteria/cor	option/solr	info/evider	image/sch	representa	to name	propose/re	elaborate	support, cc	weak/qual.	neutral ref.	weaken/di:	call into qu	call attenti	ask/inquire	tell/provid	clarify/ver	repair	explain/de:	notice	implicate	creat/add/	incorp/co-r	association	attach attr	weaken/di:	align	(traced)	inscr1 (ext	inscr2 (imp	inscr3 (cr/.	collab proc	weaken	transition/	summarize	request to	defer	commit to	nom slice	durati	weigh	width	color
2	ZD	42		•					[flat_panels/open_up]			•																														48.00	30	5	1	lightgray
4	MW	46				•			[assembly]	•																																49.40	30	6	1	lightgray
46	[assemb	42		•					[flat_panels/open_up]																•																		49.40	30	10	1	yellow
4	MW	35	•						[fit_in_aeroshell]			•																															50.40	30	5	1	lightgray
4	MW	42		•					[flat_panels/open_up]	•																																	50.40	30	6	1	lightgray
4	MW	44		•					[insul_bot_rad_up]	•																																	51.00	30	6	1	lightgray
44	[insul_bo	42		•					[flat_panels/open_up]																																		51.00	120	20	1	red
4	MW	39	•						[melting_ice]		•																															55.80	30	6	1	lightgray
2	ZD	42		•					[flat_panels/open_up]		•																																56.60	30	6	1	lightgray
2	ZD	45		•					[widget]		•																															56.60	30	6	1	lightgray
45	[widget]	42		•					[flat_panels/open_up]																																		56.60	120	20	1	red
2	ZD	47				•			[manner_1_outward]		•																															56.60	30	6	1	lightgray
45	[widget]	47				•			[manner_1_outward]																	•																56.60	30	10	1	yellow
4	MW	42		•					[flat_panels/open_up]		•																																58.00	30	6	1	lightgray
4	MW	46				•			[assembly]*		•																															58.00	30	6	1	lightgray
4	MW	43				•			[open_like_object_1]		•																																58.00	30	6	1	lightgray
3	HL	42		•					[flat_panels/open_up]			•																															59.40	30	5	1	lightgray
3	HL	46				•			[assembly]*			•																															59.40	30	5	1	lightgray
3	HL	43				•			[open_like_object_1]			•																															59.40	30	5	1	lightgray
2	ZD	48	•						[manner_1_attachm	•																																	60.20	30	6	1	lightgray
2	ZD	42		•					[flat_panels/open_up]			•																															60.20	30	5	1	lightgray
2	ZD	45		•					[widget]		•																															60.20	30	6	1	lightgray
4	MW	48	•						[manner_1_attachment]			•																															60.80	30	5	1	lightgray
4	MW	45		•					[widget]			•																															60.80	30	5	1	lightgray
48	[manner	34	•						[radiator_deployment]																																			60.80	120	20	1	red
17	RD	37	•						[cryobot_clearance]	•																																	62.00	30	6	1	lightgray
17	RD	42		•					[flat_panels/open_up]						•																												62.00	30	2	1	lightgray
4	MW	37	•						[cryobot_clearance]				•																														63.20	30	4	1	lightgray
4	MW	42		•					[flat_panels/open_up]						•																												63.20	30	2	1	lightgray

5 sec *slice* *who*

14:37:18	**48.00**	**ZD**	I understand
14:37:25	**49.40**	**MW**	take original cylinder, cut into [an assembly]
14:37:30	**50.40**	**MW**	[manner 1 assembly] "plop out" to 90 degrees.
14:37:33	**51.00**	**MW**	insulated bottom, radiating upward; minimize heat to ice
14:37:57	**55.80**	**MW**	
14:38:01	**56.60**	**ZD**	so we just have a little [widget] where the [manner 1 assembly] fall out onto the deck
14:38:08	**58.00**	**MW**	yeah, yeah, so it's like a [familiar object 1] with [manner 1 assembly]
14:38:15	**59.40**	**HL**	I see what you're saying, yeah
14:38:19	**60.20**	**ZD**	elaborates, a [widget] where you connect [and use the widget]
14:38:22	**60.80**	**MW**	yeah that's where you connect it
14:38:28	**62.00**	**RD**	How do you deploy the cryobot
14:38:34	**63.20**	**MW**	yeah don't have a picture of the cryobot, maybe I just hit it on its head

APPENDIX C. MICRO-ANALYTIC RESULTS

This appendix contains additional detail for some of the results of the various stages of microanalysis.

Network Movies / Image Sequences

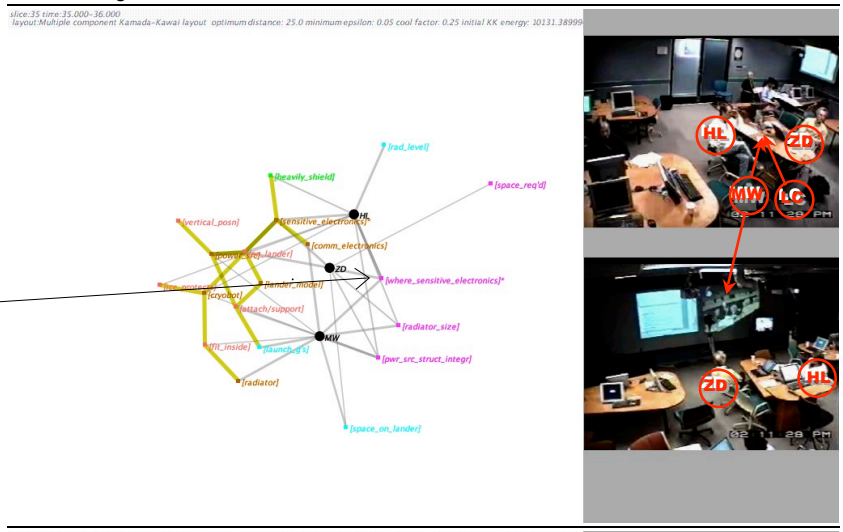
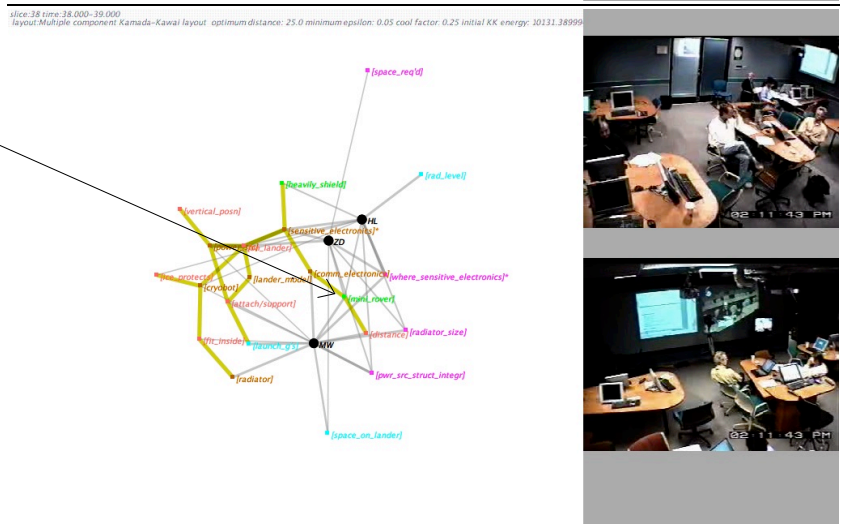
Composite movies were created of all the selected episodes. These juxtaposed the animated network diagrams output by SoNIA, alongside the two camera angles of the source video. Best appreciation of the dynamic behaviour of the real-time network representations is obtained by viewing the animations. To represent these movies in the text, I have reproduced three sequences of images below, in the following tables, with annotations describing events as they transpire.

Image Sequence #1: Episode 7

This sequence illustrates collaborative idea generation taking place primarily between four members of the team—two of whom are physically present and two who are participating remotely. Having discussed several issues, the conversation has come back to the question of how to protect sensitive electronics so they can best survive the damaging effects of radiation from the high power source. This sequence illustrates how connections between participants' utterances are made through appropriation and commonalities in image-schemas, sometimes coupled with simple transformations. This connectivity is reflected in the chain structure of the semantic network. In particular, notice the following:

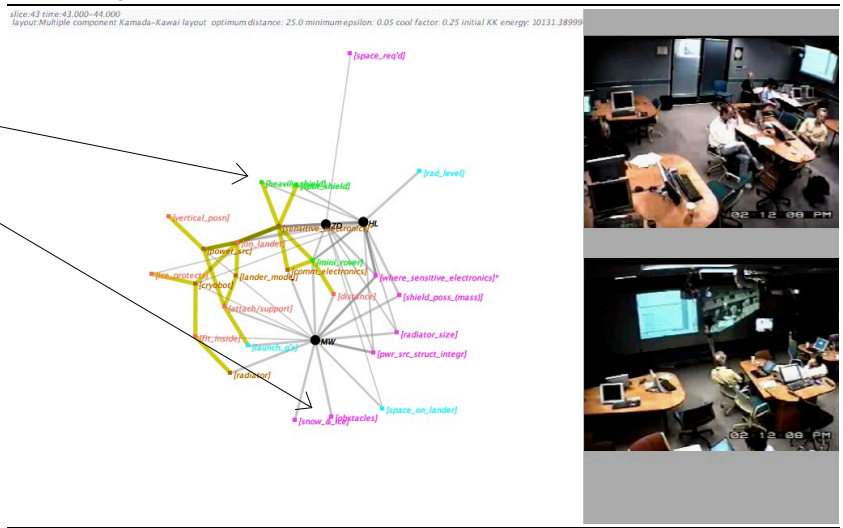
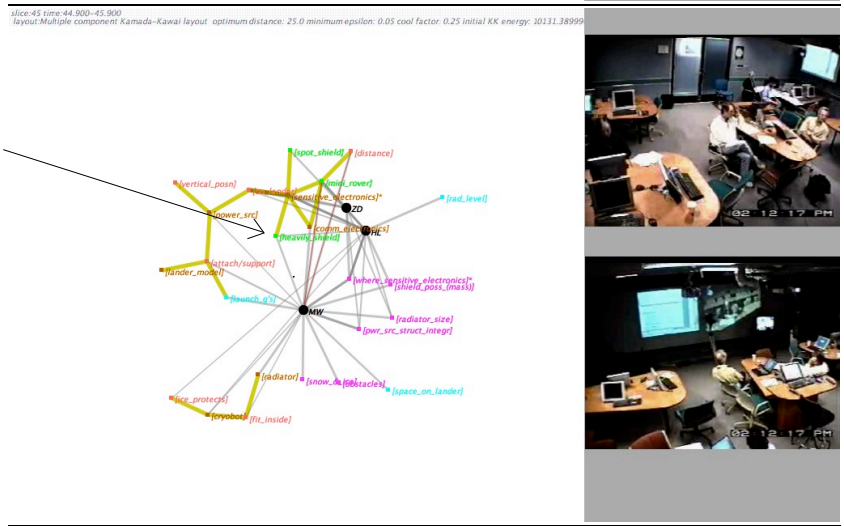
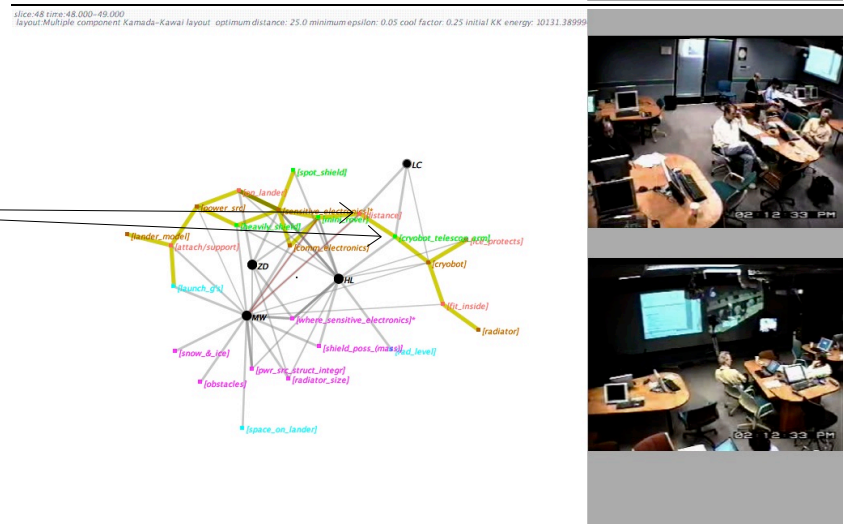
- chaining on the basis of implicit image/schema commonalities between successive contributions. Reflected by arcs in the semantic network.
- "migration" through different distance image-schemas creates an extended loop in the semantic network.
- a novel idea occurring late in the sequence—to shield an instrument package in ice—arises from a recombination of image-schemas from earlier, distinct contributions.

Table C-1. Episode 7 Image Sequence

act description	*network diagram and video*
E7 slice 35: Where will we put the sensitive electronics? MW and HL have been discussing issues with ZD and LC on speakerphone. They have returned to the question of how sensitive electronics will be protected from radiation. (Other nodes in the network are from prior conversation up to this point.)	
slice 38 (+00:15): MW mentions an earlier idea to place sensitive electronics on a "mini rover" to introduce distance between the electronics and the power system.	 [space_req'd] [heavily_shield] [rad_level] [vertical_posn] HL [sensitive_electronics]* ZD [where_sensitive_electronics]* [cryobot] [attach/support] [mini_rover] [radiator_size] MW [pwr_src_struct_integr] [radiator] [space_on_lander]

actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

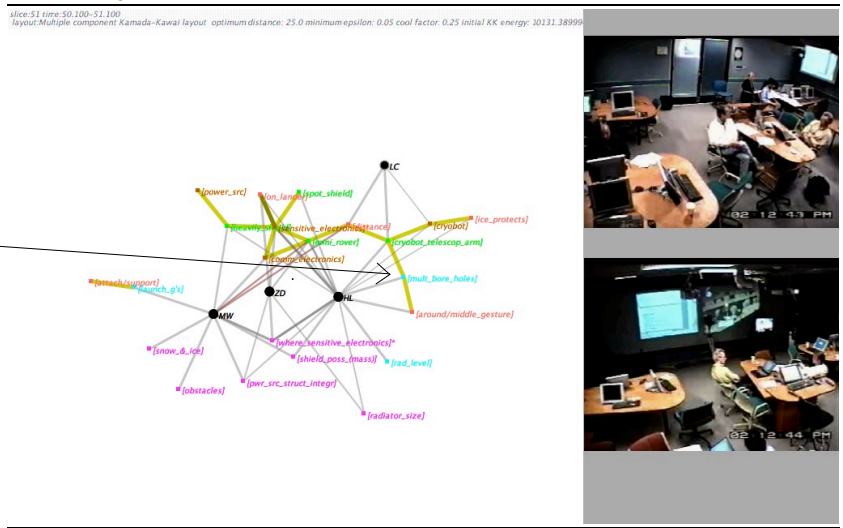
act description	*network diagram and video*
slice 43 (+00:40): HL brings up the use of localized (or "spot") shielding on the lander. MW concurs, citing the unfamiliar obstacles potentially presented by snow and ice which make the mini-rover idea less attractive.	
slice 45 (+00:49): MW elaborates, suggesting it may be necessary to consider a heavily-shielded design as a baseline for the mission.	
slice 48 (+01:05): LC interjects, asking if it would be possible to mount the cryobot (the probe with delicate sensing electronics) on a telescoping arm to reintroduce distance. HL supports the idea enthusiastically.	

actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

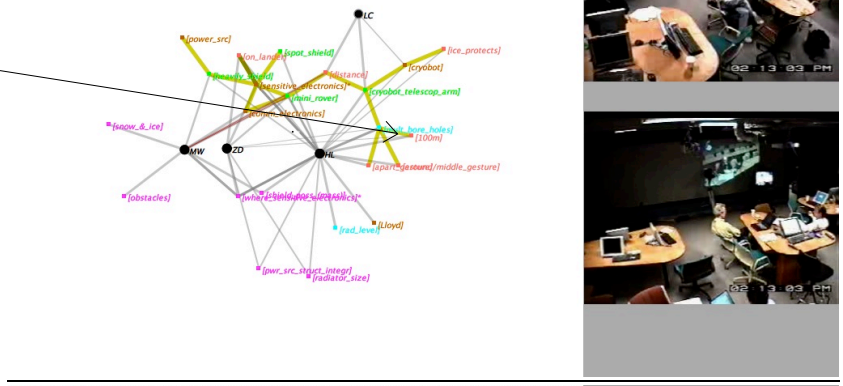
discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

act description | *network diagram and video*

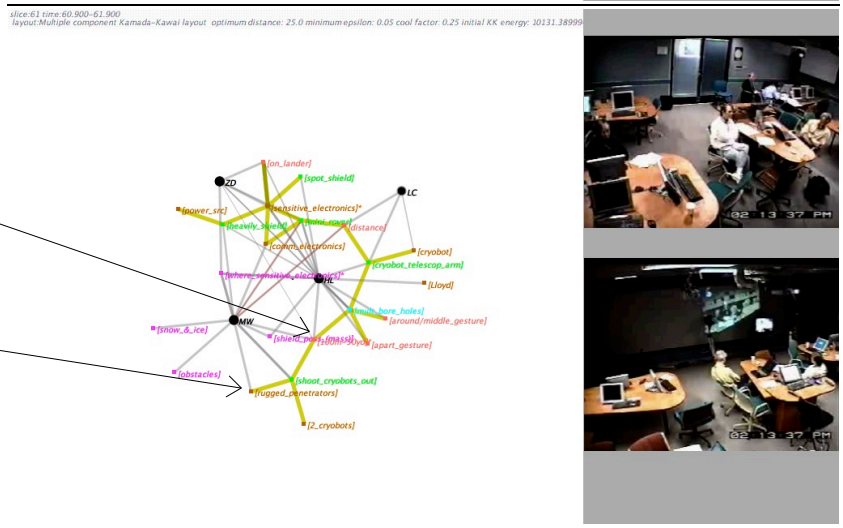
slice 51 (+01:16):
HL elaborates his support for the boom idea, referring to an earlier desire scientists had expressed for the capability to make multiple bore holes.



slice 54 (+01:35):
ZD expresses scepticism about the need for multiple bore holes, suggesting the layering of strata is likely to be the same even 100m away. HL refers to a scientist who said 100m was sufficient distance to get interesting answers from multiple bore holes.



slice 61 (+02:09):
MW asks about having two cryobots; he proposes a launcher to shoot the cryobots 50m in each direction (linking to the 100m distance schema). The proposal is greeted by laughter. MW defends the idea, citing existing designs for rugged "penetrator" probes.



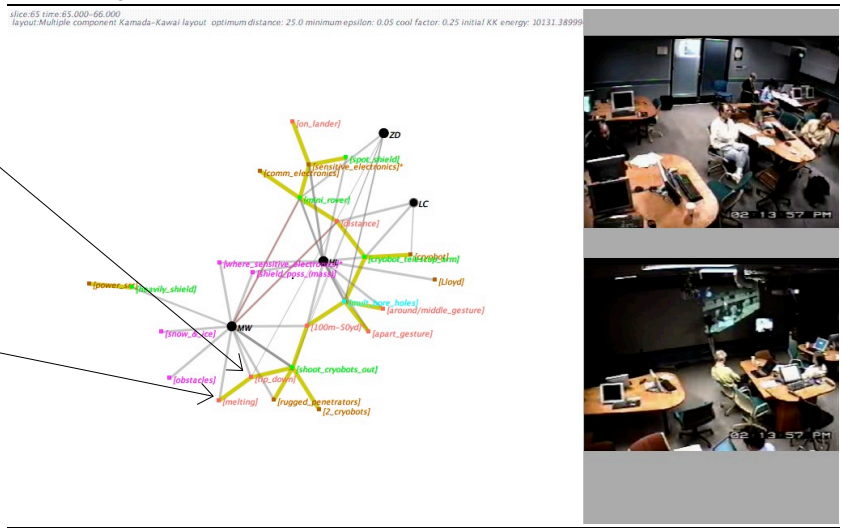
actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

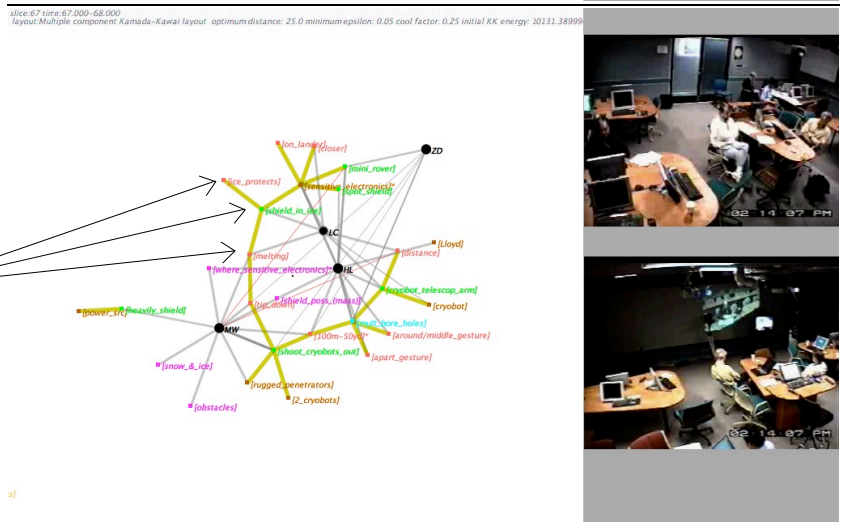
act description

network diagram and video

slice 65 (+02:29):
ZD expresses scepticism, saying the cryobots would have to land tip-down. MW defends the idea, pointing out the probes would tend to orient themselves naturally once they began melting the ice.
(introduces schema: melting ice)



slice 67 (+02:39):
LC proposes the idea of melting a package with sensitive instruments into the ice, taking advantage of the ice's natural shielding properties (links the image-schema for melting ice with the previous one of ice protecting).



actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

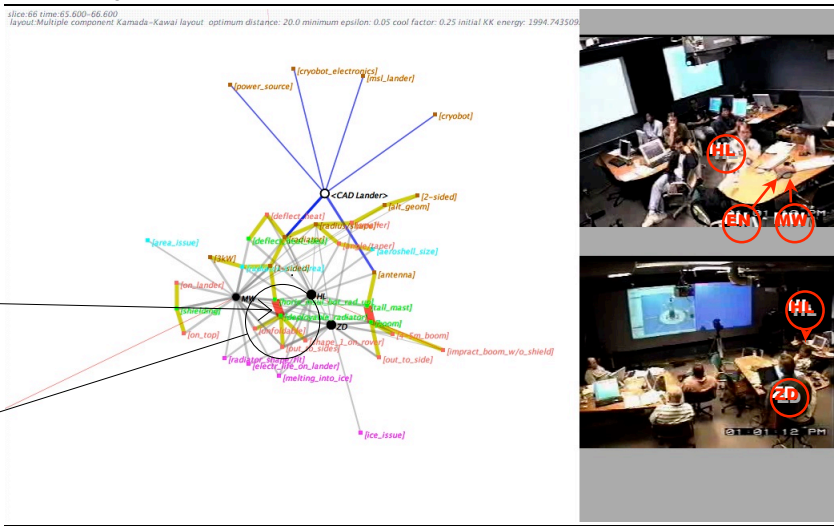
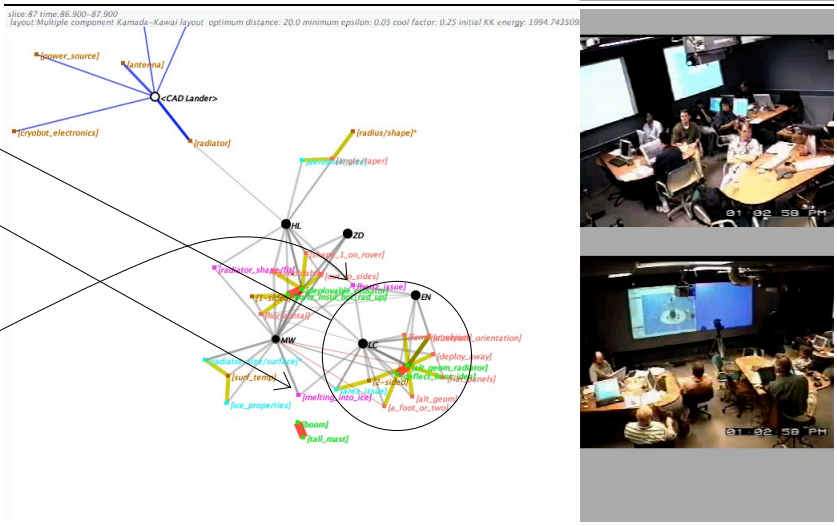
discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Image Sequence #2: Episode 12

An early stage in the radiator design in which expert opinions were divided between two alternatives. A proposal for an alternate geometry is favoured over the one ultimately adopted in Episode 39. Ambiguity related to the lack of a shared external representation appears to have played a role in one expert's inability to persuade his colleagues. In particular, notice the following:

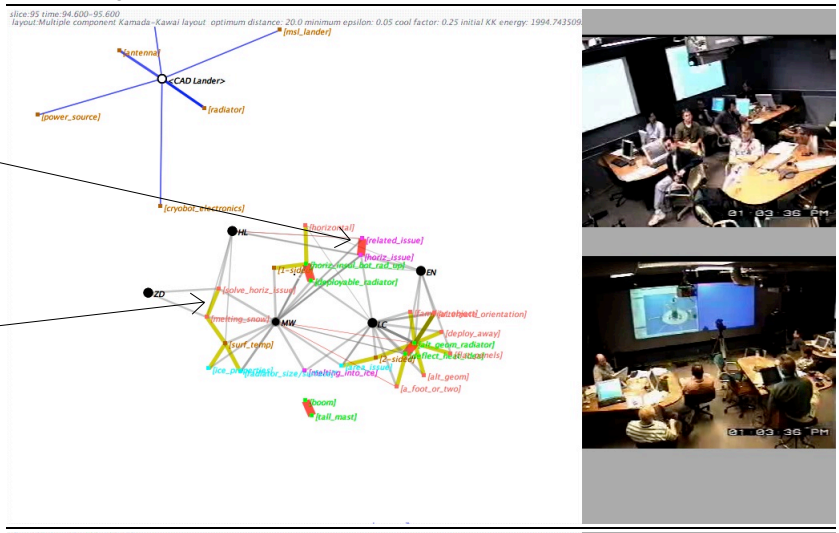
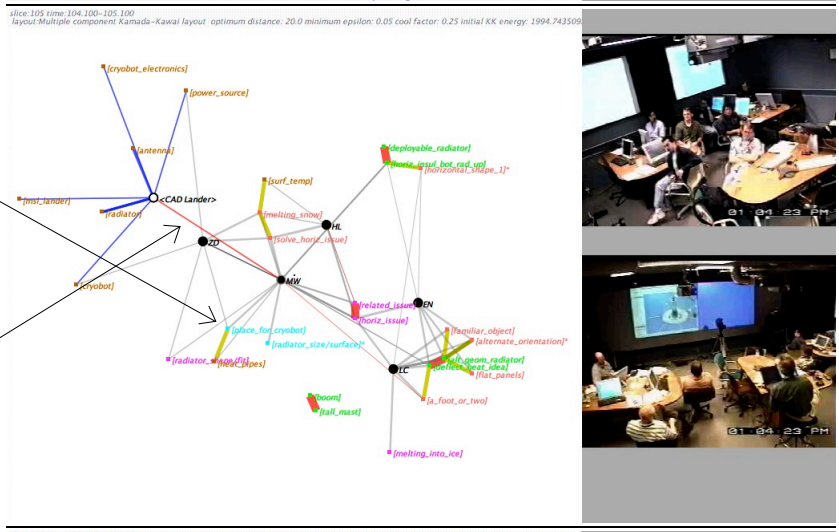
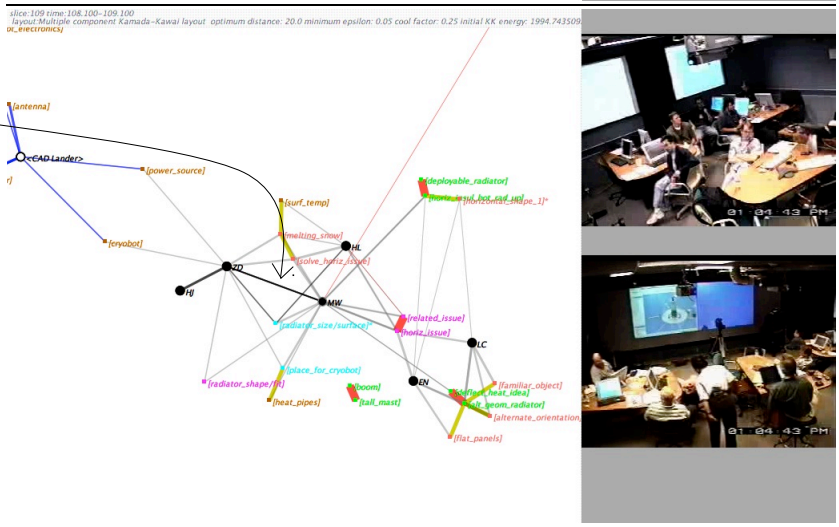
- clustering of actors as they align themselves with different alternatives and the issues they raise in advocating one or the other.
- lack of a solid consensus results in a characteristically elongated layout prior to the team leader's instruction to CAD to implement the alternative geometry.

Table C-2. Episode 12 Image Sequence

act description	*network diagram and video*
Episode 12 slice 66: ZD has broached the subject of the radiator size, concerned whether it will fit in the launch vehicle. MW reiterates an earlier proposal for a horizontal radiator, deployable, insulated on the bottom so as to radiate upward. ZD and HL receive the idea positively, clarifying the proposal for each other using several image schemas.	
slice 87 (+01:46): LC makes a counter-proposal for an alternate radiator configuration. MW raises an issue with area and ice melting, which LC seeks to address by incorporating an earlier idea to deflect heat. EN elaborates and raises an additional issue with the horizontal approach.	

actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

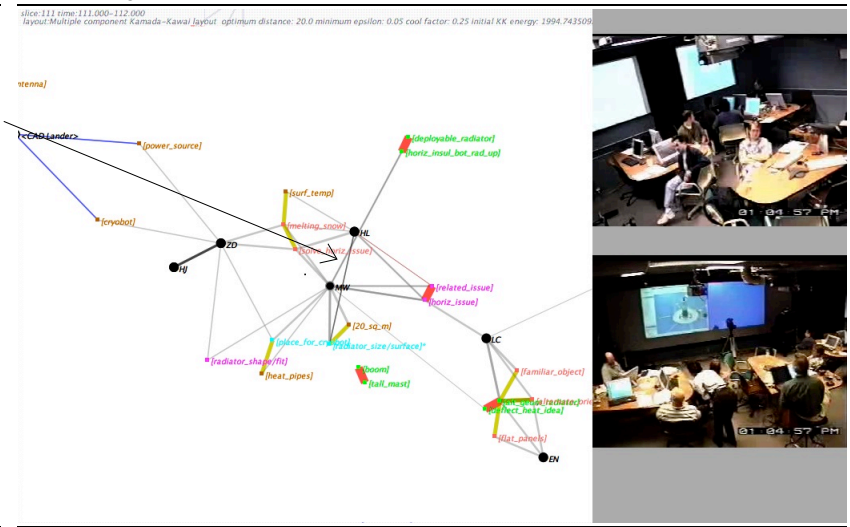
act description	*network diagram and video*
slice 95 (+02:24): MW argues benefits of going horizontal, but acknowledges the horizontal issue—even elaborating it. This prompts HL to point out how melting snow will tend to reduce the horizontal issue, to which MW and ZD concur.	
slice 105 (+03:11): ZD requests clarification about the radiator and constraints. MW answers in general terms about the flexibility of the radiator technology. At this point MW expresses confusion about the CAD (which he cannot see, is not sure what it shows) and asks for an image to be Emailed.	
slice 109 (+03:31): ZD agrees but asks MW's input first, to verify surface area and other parameters, drawing the CAD operator HJ's attention to this information.	

actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

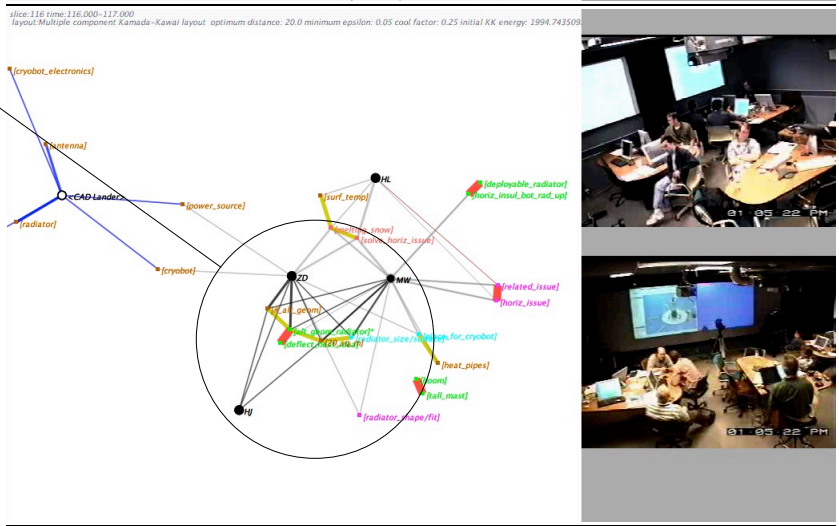
discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

act description | *network diagram and video*

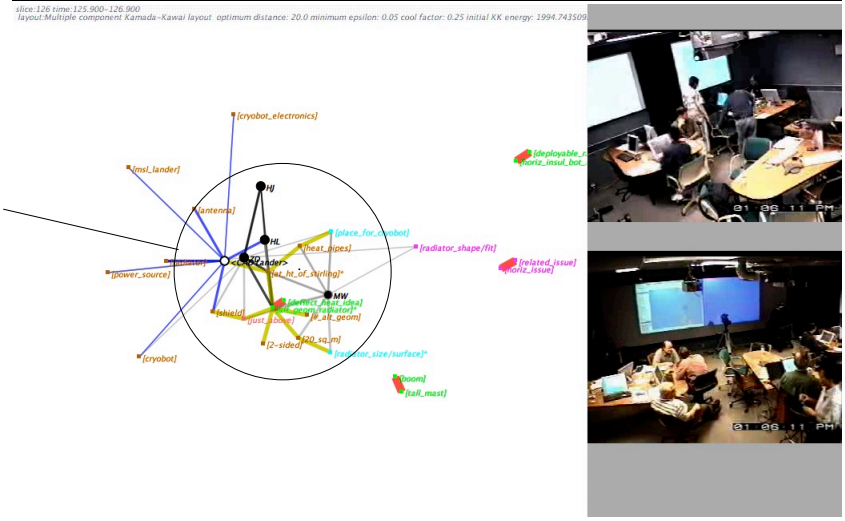
slice 111 (+03:45):
HL begins to clarify surface area and number of alternate-geometry panels. (Note how clustering has disappeared and the layout has become elongated and tenuous, reflecting the lack of cohesion around any of the options discussed.)



slice 116 (+04:10):
ZD queries MW to verify details of area, specifying the alternate geometry radiator to the CAD operator HJ



slice 126 (+04:59):
MW requests that the panels be located at a specific height relative to the power system. ZD and HL identify the relevant elements in CAD and issue instructions to CAD operator to implement the alternate-geometry panels at that location.



actor nodes: ● *participant present* ◉ *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

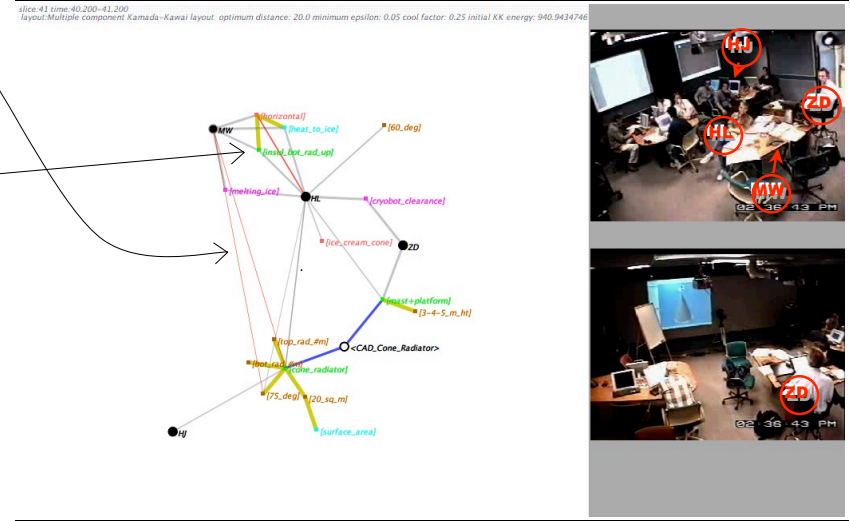
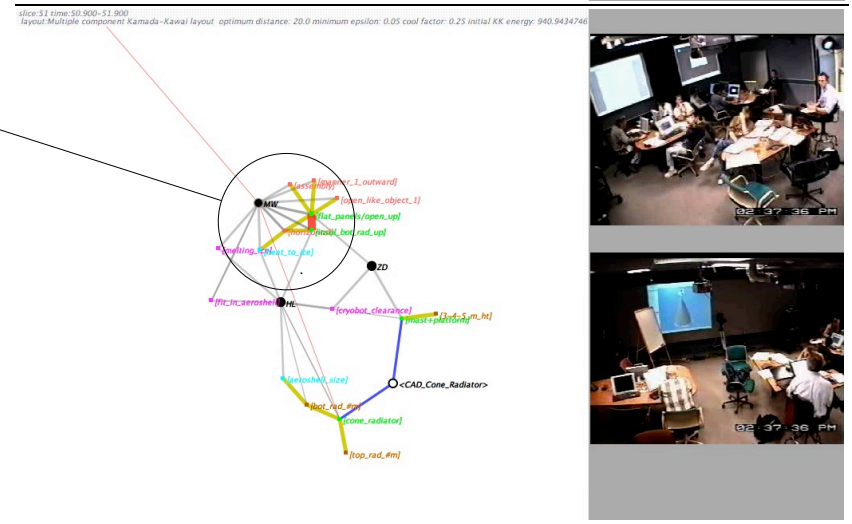
discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Image Sequence #3: Episode 39

One expert objects to an interim design for a major component (the radiator) and re-introduces an alternative previously rejected. Discussion and repair triggers a period of shared whiteboard drawing with eventual convergence on a new design based on the alternative proposal. Instructions are given to the CAD operator to change the model. In particular, notice the following:

- distancing caused by strong disagreement
- the locus of activity shifting from the CAD model to the whiteboard drawing
- entrainment of several participants around the whiteboard, ultimately resolving the disagreement and collaboratively elaborating the initial proposal
- gestural exchanges used to reinforce the image-schema content of the language

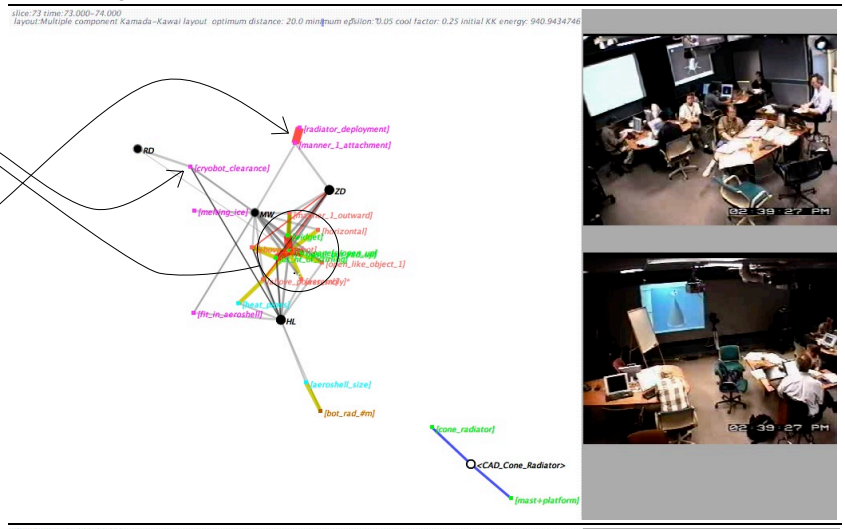
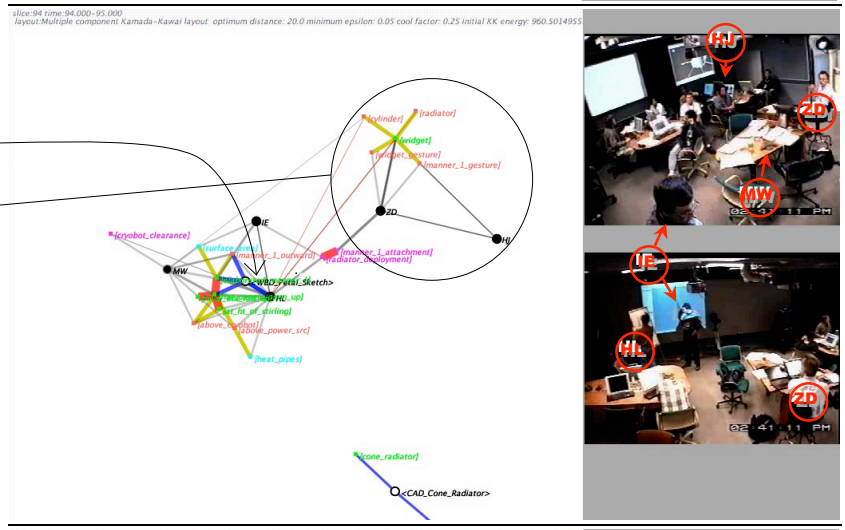
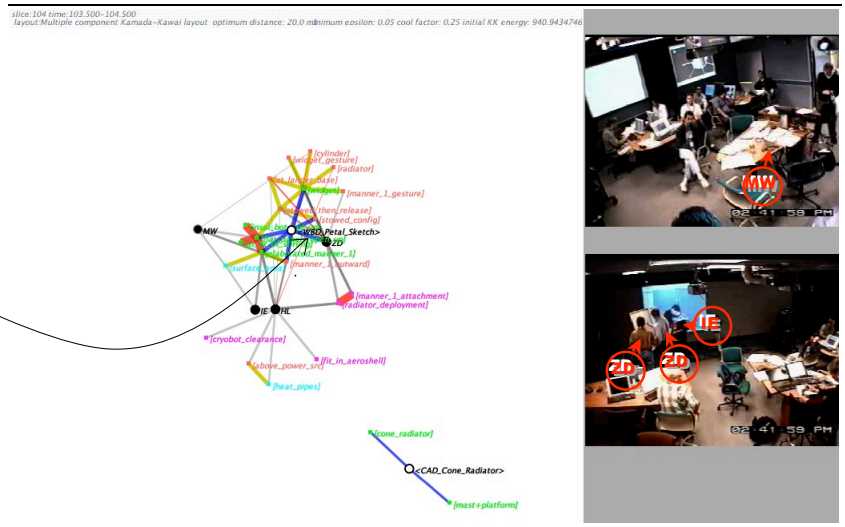
Table C-3. Episode 39 Image Sequence

act description	*network diagram and video*
Episode 39 slice 41: HL and ZD describe the CAD model. MW objects to the cone radiator design, and proposes (for the third time[1]) a horizontal alternative.	
slice 51 (+00:55): MW explains his proposal and elaborates with several image-schemas. ZD and HL respond favourably	

[1] MW proposed a horizontal radiator configuration first in Episode 12 (see sequence #2), and again in Episode 18 (not subjected to microanalysis). After the second proposal a conical form was agreed upon in principal; it is the implementation of this cone that MW rejects at the start of this sequence.

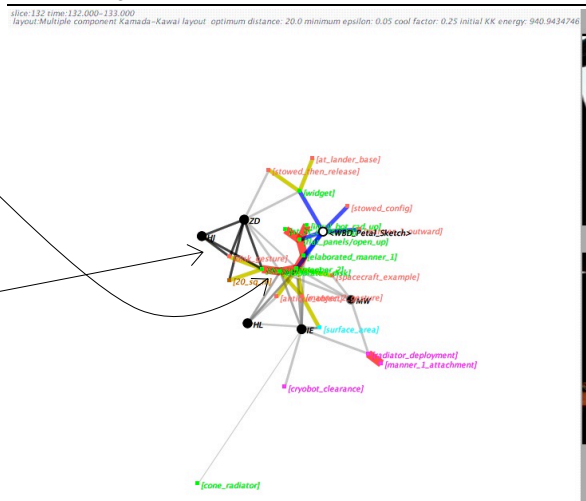
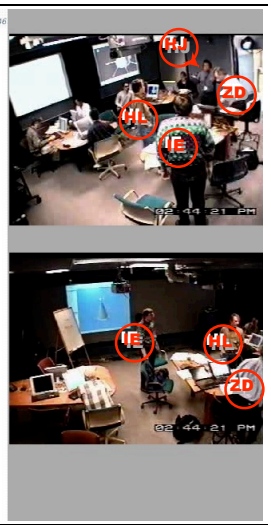
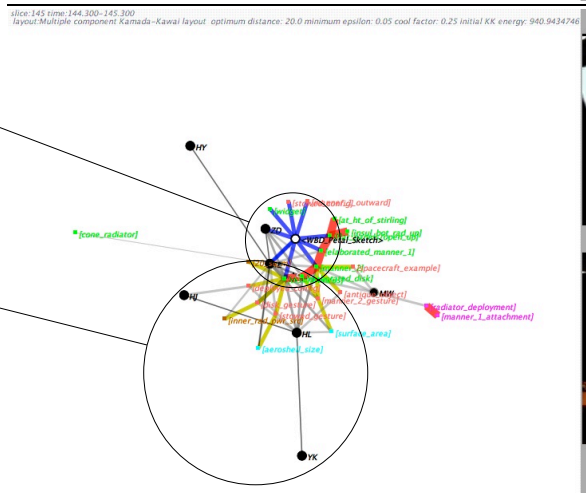
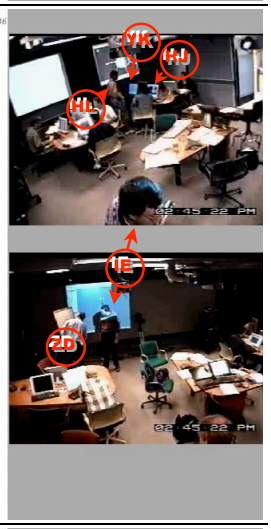
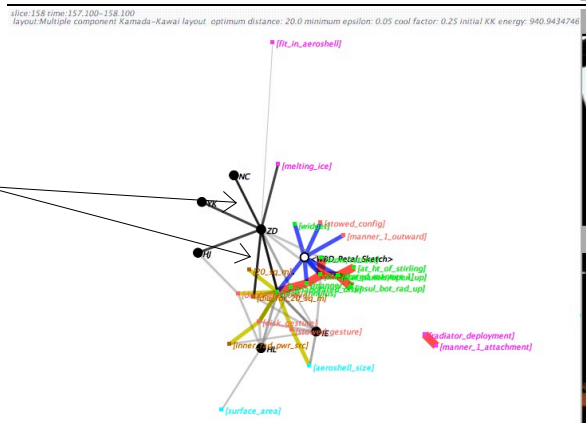
actor nodes: ● *participant present* ◉ *remote /audio-visual* ◉ *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

act description	*network diagram and video*
slice 74 (+02:44): ZD and HL collaboratively develop the idea with MW in response to an issue raised by RD. ZD is concerned with mechanical details of deployment and proposes a widget as a solution.	
slice 94 (+04:24): HL disagrees, rejecting the need for a widget. He moves to the whiteboard and begins drawing to clarify the proposal, where he is joined by IE. ZD turns to enlist HJ in a gestural exchange to support the widget idea.	
slice 104 (+05:16): ZD, listening to HL and IE takes another opportunity to interject his widget idea, this time moving to draw at the whiteboard as well.	

actor nodes: ● *participant present* ◉ *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

act description	*network diagram and video*
slice 132 (+07:38) ZD, IE, HL and MW discuss a simplified form for the deployed radiator and a specific height at which it should be positioned. ZD gives instructions to HJ to implement this in the CAD model, which HJ agrees to do.	 
slice 145 (+08:39): two distinct conversations are now taking place in parallel: IE and ZD have returned to the whiteboard, while HL is reviewing instructions with the CAD operators HJ and YK.	 
slice 158 (+09:45): ZD instructs the CAD operators HJ and YK to implement the radiator with a specific area and report what the required diameter will be. He asks the thermal analyst NC if he is prepared to use that information to address the question whether waste heat will melt the ice under the lander.	 

actor nodes: ● *participant present* ◉ *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Total Degree and Overall Alignment

The total degree metric is the sum of the degree of all nodes in the network at any given time slice. It was developed as an index of the overall level of alignment expressed by participants at any particular point in time. Juxtaposing a graph of total degree with a timeline showing key events in each episode shows a good correspondence between peaks in total degree and certain key outcomes, with some interesting exceptions as described below.

Inclusion of Inscription in Total Degree

As discussed in the main text, semantic relationship and collaborative product arcs do not reflect alignment between participants and discourse; as a result the metric is applied only to the actor-discourse portions of the networks for each episode. It was also necessary to consider the most appropriate way of addressing inscription. On one hand, clear isolation of predictor and criterion variables might argue for keeping inscription and discourse alignment separate. On the other, drawing activity appears to be a legitimate reflection of the level of energy in a design discussion. Specifically, with respect to Episode 39 for example, elevated levels of whiteboard drawing accompanied a reduction in the frequency and complexity of verbal utterances. Since the video record did not allow coding drawing acts with a granularity comparable to that of speech, the level of activity reflected in the total degree appears lower than it might otherwise be; this situation would be worsened if inscription were excluded entirely. I evaluated the impact on total degree of inscription arcs set to different strength and duration values, as shown below, ranging from zero to twice the strength used in generating the real-time and cumulative layouts. I selected a uniform, intermediate strength (5) and a duration equivalent to that of design discourse (30) as a conservative compromise, to register inscription without having an undo effect on total degree in most cases.

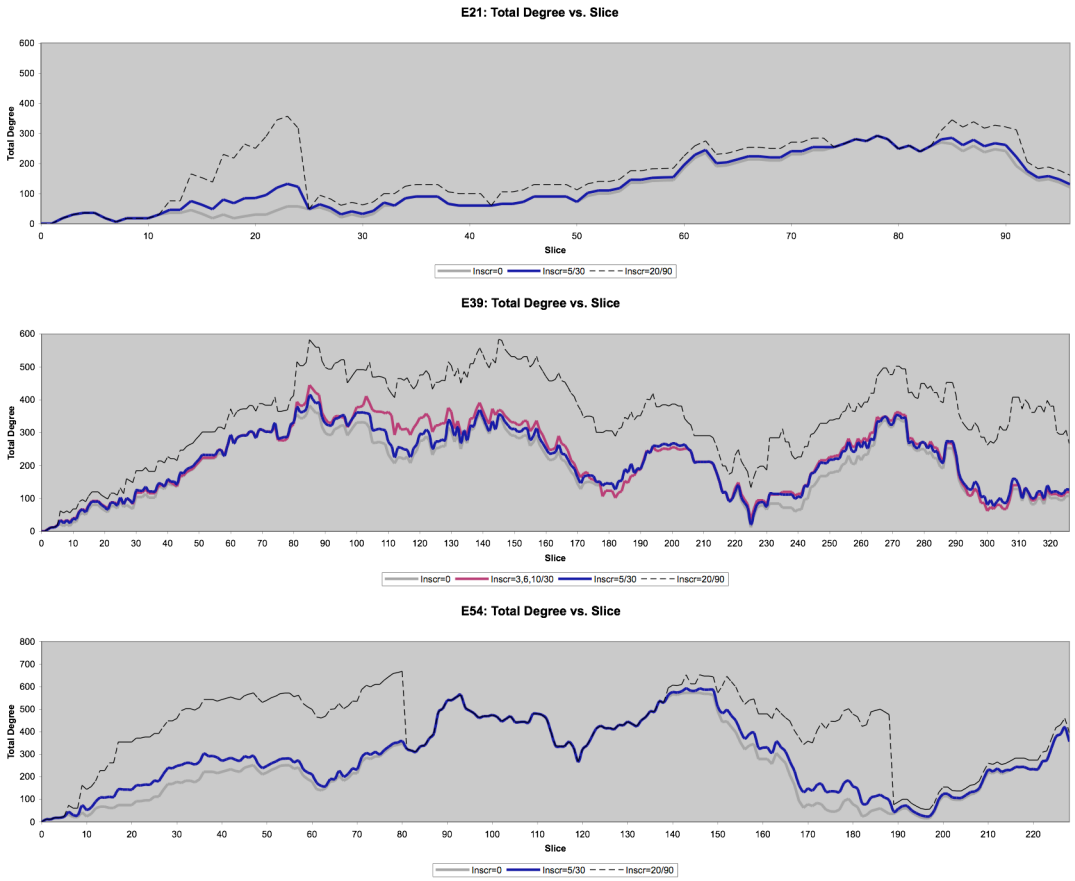


Figure C-1 Sensitivity of Total Degree to Different Inscription Strengths
Three episodes exhibiting different degrees of representational activity were compared with regard to the inclusion of inscription arcs in the total degree metric. Values for inscription strength range from zero to 20 (twice the strongest value used in real-time animated layouts); duration ranges from zero to 90 slices (with 30 slices being the nominal value for discourse). The darkest curve corresponds to the values I chose to use—with strength (5) and duration (30 slices) equivalent to those for relatively strongly-aligned discourse.
The additional curve shown for Episode 39 depicts graduated inscription strength comparable to the scheme I eventually adopted for real-time and cumulative aggregate layouts (3 , 6, 10), also with a duration of 30 slices.
Sharp transients in the strongest, long duration inscription curve in Episodes 21 and 54 correspond to points at which the shared display was switched off or changed to a new representation.

Comparability of the Total Degree Metric across Episodes

It is generally desirable for metrics to be normalized in some way to facilitate comparisons across contexts, and with results that may be obtained by other researchers. The total degree depends upon the strength scale for alignment as coded in the discourse, the number of discourse nodes coded per utterance (the granularity of coding), and the temporal width of the aggregation interval (or the nominal arc duration). It would be relatively easy to normalize for the arc strength scale and the aggregation interval. Comparisons between the work of different analysts would require steps to ensure a comparable granularity of coding. Because the results presented here were developed by a single analyst, in an iterative manner to ensure consistency, the total degree metric should be valid for internal comparisons.

It would also be easy to normalize the total degree metric for the number of actor nodes, however I decided against this. Even in cases when fewer actors were directly participating, the density of the conversation in terms of the number of utterances, discourse elements and the level of alignment expressed was often still quite high. It seems reasonable that less dense conversations—regardless of the number of actors—legitimately reflect a lower level of alignment.[3]

Discourse Betweenness and Mutual Engagement

Discourse betweenness is the sum of the flow betweenness centrality values for all discourse nodes, compared to that for all nodes (discourse plus actors), expressed as a percentage. It was developed as an index for mutual engagement, or the extent to which discourse nodes form bridges between actors in the actor-discourse networks. The flow betweenness centrality metric is significantly more complex computationally than degree centrality (Freeman et al. 1991). It requires considering nodes one pair at a time and taking into account every path through the network connecting each pair. A maximum flow through the network between each node pair is calculated by treating each arc's strength as a capacity. As in the case of a pipeline, the flow along any given path is limited by the lowest capacity connection (i.e. weakest arc) in the path. Contributions to the maximum flow are identified, and a flow value is attributed to every node along each path. As the procedure is applied to every possible pair of nodes, those nodes that lie on a larger number of the maximum-flow paths will accumulate a higher value for flow betweenness.[4]

The structural properties assessed by flow betweenness centrality and degree centrality are significantly different (Freeman et al. 1991, Freeman 1978, Scott 2000, Wasserman & Faust 1994). Particular aspects of the behaviour of discourse betweenness compared to total degree are described below, based on differences in the underlying metrics of flow betweenness centrality and degree centrality. These differences are consistent with the idea of mutual engagement as distinct from overall alignment. On balance however, the flow betweenness metric was found to be a problematic basis for evaluating mutual engagement, as discussed at the end of this section and in the main text.

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[3] Situations of direct conversational interaction may be somewhat self-normalizing in that they become unintelligible if too many participants try to speak at once, and uncomfortable if significant periods of unbroken silence occur. Conversations are essentially limited by the bandwidth of the conversational channel. In larger groups each individual participant may contribute less, or more of the group may be relegated to marginality. In practice such groups may also break into multiple, parallel conversations. This would represent an expansion of the channel, and if parallel conversations were coded a higher total degree would result. Because parallel conversations were not coded this consideration is beyond the scope of this research.

[4] UCINET versions 5 and 6 use different algorithms to calculate flow betweenness. The results presented here were produced with the version 5 algorithm.

Discourse Betweenness and Total Degree as Independent Measures

While high mutual engagement requires at least some level of common alignment between actors, strong overall alignment does not necessarily entail high mutual engagement, since participants may be aligned with substantially different elements of discourse. Systematic disagreements, where one actor distances themselves from elements the other is strongly aligned with and vice versa, involve no strong bridges between actors. A large number of discourse nodes linked only to one actor further reduces discourse betweenness, since such discourse nodes have zero flow betweenness themselves (because they are not *between* anything). They do however contribute to the flow betweenness of the actor, increasing the score for actors relative to discourse (thereby lowering the discourse betweenness). These effects are visible below in Figure C-2.

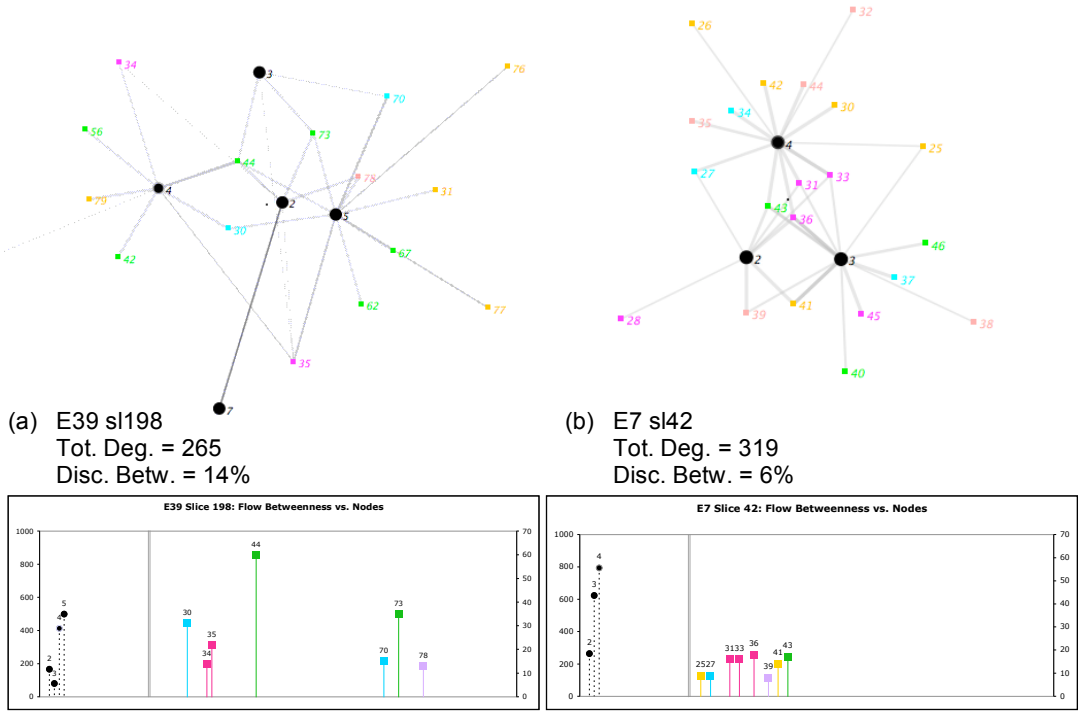


Figure C-2 Independence of Total Degree and Discourse Betweenness
Flow betweenness is a measure of the extent to which nodes lie on maximum flow paths between other nodes. The discourse nodes in (a) E39 slice 198 carry a significantly higher proportion of the flow betweenness than those in (b) E7 slice 42, though the latter has a higher total degree.

Greater Structural Sensitivity of Discourse Betweenness

The flow betweenness metric is considerably more sensitive to the precise structure of network connections than degree centrality, such that individual arcs may have a significantly greater impact. This sensitivity is not necessarily a problem since it means the

metric can respond dynamically to changes in design discourse, such as illustrated in Figure C-3.

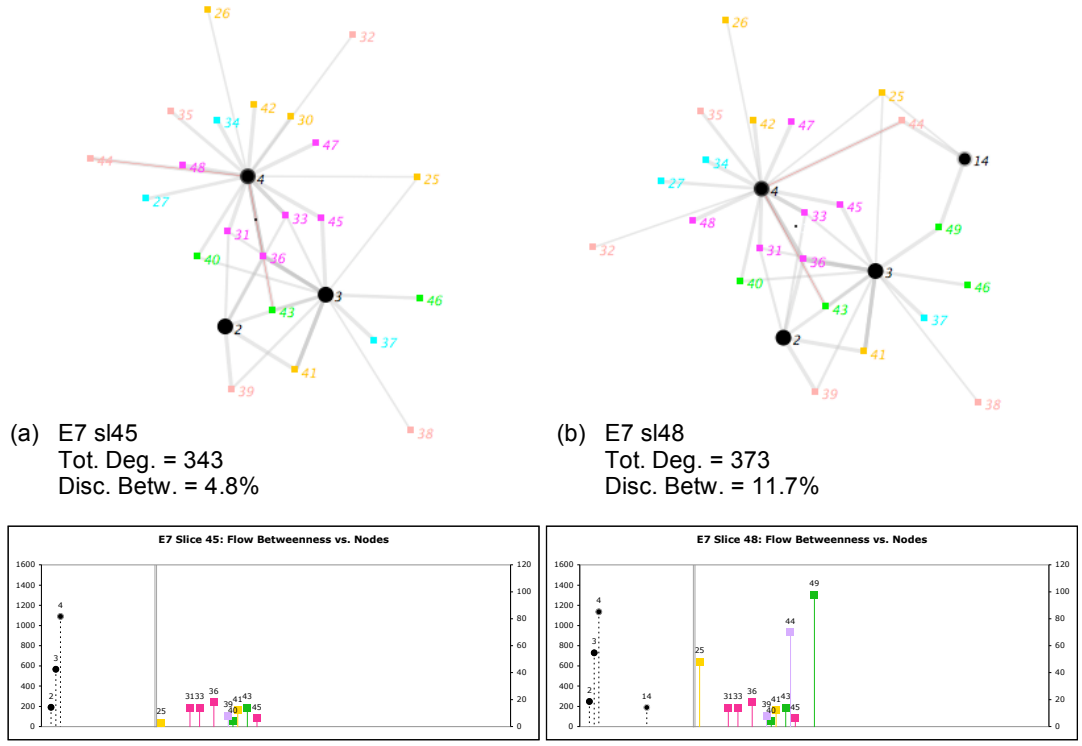


Figure C-3 Dynamic Response of Discourse Betweenness Metric
In (b) E7, slice 48, actor 14 has just proposed mounting sensitive cryobot electronics on a telescoping arm—a significant proposal in the overall course of the episode. Compared to (a) E7, slice 45, the flow betweenness metric has responded much more strongly than the total degree metric to this development.

The potential sensitivity of discourse betweenness to individual arcs made it desirable to differentiate the effects of short term, neutral acts (such as questions and information movement) from design discourse. For this reason I adopted a sampling strategy to evaluate discourse betweenness at additional points three slices before and after the check slices I initially identified.

Additionally, I noted that very sparse networks corresponding to lulls and periods of low interaction tended to yield somewhat extreme and erratically fluctuating values for flow betweenness. To detect this situation, I implemented a straightforward measure of the relative level of shared discourse. The percentage of shared discourse nodes' contribution to the total degree was calculated for each slice and is depicted in the graphs in Chapter 6 as a grey ghost bar behind the flow betweenness value. A shared discourse total degree fraction of ~25% was empirically found to be a threshold below which flow betweenness values might be misleading.

Problematic Aspects of the Flow Betweenness Metric

Overall, the results show a relatively higher discourse betweenness to occur in conjunction with periods of focused discussion and convergent interaction. That this is also true of periods dominated by communicative repair is consistent with an understanding of this metric as a reflection of mutual engagement as distinct from alignment. However, while the metric does appear to reflect differences between episodes relating to mutual engagement, it responds to more than just the "bridging" effect of mutually-engaged discourse. It also depends upon the number of unshared discourse nodes connected to each actor, the relative numbers of actor and discourse nodes, and sometimes seems to be disproportionately influenced by single discourse node bridges to relatively less engaged actors. An example of this behaviour is seen in Figure C-4.

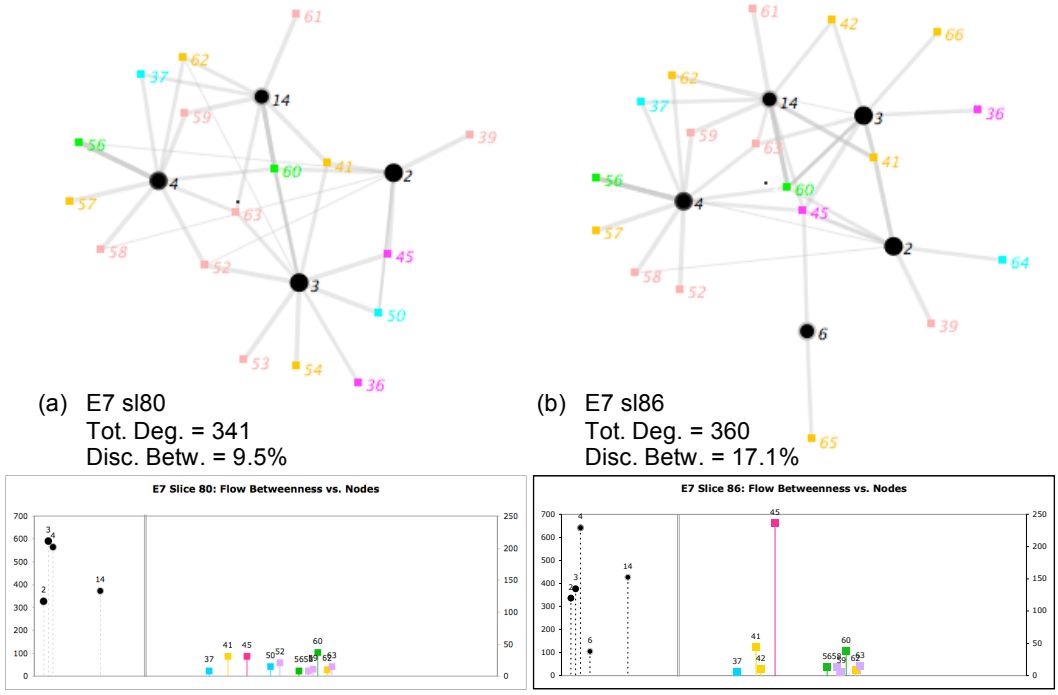


Figure C-4 Response of Flow Betweenness to a Single-Node Bridge to a Less-Engaged Actor
Does the additional engagement of actor 6 in slice 86 justify the significant increase in flow betweenness score of node 45 compared to node 60? As can be seen below, increase in the degree of node 45 indicates that other actors in addition to actor 6 have also aligned more strongly with it, with an average strength increasing from 3 to 5.

actor	*slice 80 degree*	*slice 86 degree*	*discourse*	*slice 80 degree*	*slice 86 degree*
2	31.0	29.5	41	16.0	16.5
3	51.0	37.5	45	12.0<<	25.0<<
4	50.0	55.0	60	19.7	19.7
6	~	10.0	63	15.0	15.0
14	38.7	48.2			

Review of Freeman et al's (1991) discussion of the metric makes this behaviour more clear. Conceived for single-mode networks (i.e. in which all nodes represent equivalent actors), the

metric is based on the idea that nodes lying on flow paths between a large number of other nodes have the capacity to control or limit information passing between these other nodes. This is particularly true when there is only a single path linking a subset of nodes in the graph. The metaphor of nodes as *control points* for information flow is quite different from my notion of discourse nodes acting as *bridges* between actors.

It can be argued, and is frequently the case in small groups that the sudden entry of a new participant, prompted by a particular topic shift, may signify a greater significance of that topic to the group. It also may be the case that an increasingly energetic conversation focused around a particular topic may draw contributions from previously unengaged participants. While it is possible to relate the response of the metric to such seemingly favourable interaction patterns, it is uncomfortable to begin to rationalise the behaviour of the metric in terms of the phenomena. It is preferable to start with the phenomena of primary interest and to construct the metric to respond specifically and selectively to them.

The flow betweenness metric appears to preferentially score nodes lying on unique flow paths between other nodes, compared to nodes on multiple or redundant flow paths. While this is consistent with the metaphor of control, it is not consistent with the conception of discourse nodes as bridges. This mismatch between the flow betweenness metric and the phenomena of interest in comparing these episodes has led to the proposal of a more appropriate metric and its formulation and testing for future work. (This is discussed in the methodological reflection chapter, with additional details presented in Appendix E.)

APPENDIX D. MACRO-ANALYTIC RESULTS

This appendix contains transcript extracts cited in conjunction with the presentation of macro-analytic results.

Sensitive Electronics

The following excerpts are for the Sensitive Electronics thread. This comprised discussion regarding how best to protect scientific instrumentation and other sensitive electronics from the damaging effects of radiation generated by the compact high-power source (CHPS). This thread included emergence of one of the essential, innovative design features: a platform for sensitive electronics at the end of a vertical mast.

1097: ZD: […] By the way ... this thing on the top. Is that you're antenna basically?
1098:
1099: HL: [to agency participants] is that your antenna ... on the top there?
1100:
1101: EN: That's not our antenna, but that might be a good place to put one if it can survive up there.
1102:
1103: HL, ZD (together)
1104: Yeah.
1105:
1106: ZD: And how much did you say the radiation was up there?
1107:
1108: MW: Oh no. The antenna that sits up on top of the structure there?
1109:
1110: ZD: Yeah.
1111:
1112[5]: MW: That is a temporary antenna to get communication with earth before you deploy out the little rover that runs away with the real antenna. The electronics [there would have inadequate life without necessary shielding] [6]. That's why what EN is about to do is so very important. [shielding is necessary] so you can have components mounted on the lander and not have to deploy them.
1113:
1114: HL: (and ZD) Yeah.
1115:
1116: ZD: Or maybe we can have some booms and I asked HJ to look into that and I'm sure he has.
1117:
1118: HL: Yeah, that antenna can certainly be <u>deployed on a fairly tall mast</u>.[7]

[5] The numbers preceding the participant's initials are paragraph numbers from the transcript; because this transcript was double-spaced, a blank line occurs between successive turns.
[6] Certain specific information was redacted at JPL's request, on the basis of export control regulations. This information was replaced with a more general descriptor enclosed in square brackets. The more general descriptor or a variant is used for labelling in the network diagrams and node descriptions.
[7] In these extracts, I employ underlining to draw the reader's attention to key parts of the excerpt, not to reflect any particular emphasis by the speaker.

...
1128: ZD: We should think sort of in the 4-5m-range boom, maybe out to the side. But of course, if we melt into the ice 'til [ice issue], then we've got a little problem then.

Excerpt D-1 Episode 12 transcript paras. 1097-1128

2954: HL: (looking at CAD) You can mess with the size of that platform ...
2955:
2956: ZD: Yeah, you're not at all limited by that ... just make it as large as we need.
...
2962: HJ: So then we look at how on the left side <unintelligible> ... but we need to talk about if I have everything that you need
...
2968: HJ: ... because right now I got {the CAD in a transitional state}.
...
2974: ZD: We will, we'll get back to that.
2975:
2976: HL (referring to CAD): Unless, wait a minute.. We don't want to make the platform too big, though, he's got a good point. If he makes it a [rearrangement similar to transition state] platform, that keeps the shield [more effective]. So maybe that [rearrangement] idea might not be bad.
2977:
2978: ZD: No it's not bad at all.
2979:
2980: HL: Cause you're [more effectively utilizing the shield]. That's good. We're talking about where to place the electronics (addressing remote participants on the speakerphone).

Excerpt D-2 Episode 18, transcript paras. 2954-2980

Radiator Configuration

MW initially proposed the horizontal radiator configuration in Episode 12. HL offers a descriptive comparison based on a previous, unrelated rover design, seen by all and greeted by humour. LC makes an immediate counter-proposal for an alternate orientation.

1152: HL: You're probably not going to be able to get by with that shape to fit it into the backshell of your aeroshell design so I would imagine that it would be .. it would come up maybe at a steep angle and then taper over into a shallower angle.
1153:
1154: MW: What I'm seeing is that the real solution is going to be maybe a deployable radiator with serious insulation on the bottom side facing upward and letting all the radiation going up.
1155:
1156: ZD: When you say deployable ... meaning [a different deployment idea] or ?

1157:
1158: MW: No, I'm sorry ... just unfoldable ... [means 1] with an arm ...
1159:
1160: HL: Yeah, it would look kind of like the [shape 1] on the rover that we had ...
1161:
1162: ZD: Oh out to the side ...
1163:
1164: MW: Yeah, there you are ... off to the sides ... right.
1165:
1166: ZD: Exactly.
1167:
1168: MW: Maybe a [means 2] deployment. On the bottom ... it would be a one-sided radiator again, but the bottom would be heavily insulated or ... I mean insulated well ... and the top half would be doing all the radiating.
1169:
1170: LC: Why don't you just make it [alternate geometry] that ... two-sided ... that have a better [area issue] to the [surroundings].. that's further away from ...
1171:
1172: MW: Say that again.
1173:
1174: LC: Like 3 or 4 [forms of alternate geometry] like [shape 1] that deploy further away from the reactor and don't ... don't reflect as close in all in the same area to the ice ...

Excerpt D-3 Episode 12, transcript paras. 1152-1174

MW expressed scepticism about LC's proposal citing technical considerations, and a brief discussion of issues and relative merits of the two approaches ensued.[8] However, the team leader, ZD, was apparently confused by the fact both MW and LC used the same descriptive term (designated "shape 1") for their competing proposals.

1196: ZD: I'm trying to understand what you're trying to do. You want to have it [alternate orientation]... basically [shape 1]?
1197:
1198: EN: Yeah. Flat panels coming out that are [alternate orientation]...
1199:
1200: MW: Yeah ... Well then ...
1201:
1202: LC: Like [a familiar object].

Excerpt D-4 Episode 12, transcript paras. 1196-1202

LC's description of the alternate geometry and comparison to a familiar object[9] supported by EN was still confusing to ZD. Since LC had also said yes to "shape 1"—which was associated with the initial proposal and seemed inconsistent with description of the familiar object—ZD again requested clarification:

...

[8] See also the Episode 12 image sequence summarized in Table 6-7 and included in Appendix C, which shows network diagrams depicting this exchange.
[9] Again, the specific descriptions were redacted by JPL on the basis of export control concerns.

1224: ZD: Like [alternate geometry/familiar object] is that what I'm hearing ... or [shape 1]?
1225:
1226: MW: (laughing) ... It's like what Richard Gere said to Julia Roberts, what would you like it to be? In other words with this particular radiator design it's a capillary pump loop or loop heat pipe, so you can really pipe heat where you need it and put the panels where you can so we'd work with the cryobot folks to put them out where you want to.
1227:
1228: ZD: Okay.
1229:
1230: MW: The picture that you have up on the board right now ... I can't see it. Is there anyway to make a JPEG out of it and e-mail it to folks so we could look at it .. not right now but after the meeting so I can design around it?
1231:
1232: ZD: Oh yeah sure. We also want you to give us some input so we can start thinking about it ... so what was the surface area?

Excerpt D-5 Episode 12, transcript paras. 1224-1232

When, in Episode 39, MW reintroduces his horizontal radiator proposal (after the alternate geometry had eventually been rejected for yet another interim design in Episode 18), he has evidently made a point of preparing an effective verbal description of the shape he has in mind.[10] This time he refers to a "different familiar object" (in the extract below, unrelated to the familiar object mentioned by LC) having a completely different form and symmetry than the "shape 1" initially invoked by HL to describe the horizontal proposal:

3135: MW: It sounds like you haven't made too much progress in terms of getting towards the horizontal with this approach.
3136:
3137: HL: Getting towards the horizontal?
3138:
3139: MW: We don't want to shine heat on the Martian ice, so we were trying to make it horizontal, so we could insulate the bottom of it.
3140:
3141: HL: Right.
3142:
3143: MW: And have it radiate only upward ... and it sounds like we're not making much progress .. we started out with basically a vertical cylinder and we've gotten sort of a cone ... but not much of a cone, we've only got it added what ... 15 degrees or so?
3144:
3145: HL: Yeah you're right actually ... that's uh ... this represents pretty much a uh .. probably the best you can do ... actually ... as far as the cone goes on this lander because it's taking up most of the bottom radius of the lander.
3146:
3147: MW: So the question now is ... instead ... can you just have your radiator kind of angle out into flat panels ...

[10] MW later indicated he had prepared a PowerPoint image to send, but felt it became unnecessary once he was confident the others fully grasped and accepted his idea.

open up ... say like a [different familiar object] that opens up ... except for the bottom, [it opens in manner 1] outwards ... what's another good example?

3148:

3149: ZD: I understand.

3150:

3151: MW: Say we started with our original radiator.

3152:

3153: HL: Yeah.

3154:

3155: MW: Cut it into , [an assembly] okay?

3156:

3157: HL: (and ZD) Uh huh.

3158:

3159: MW: And now, instead of putting a [type of material] on the outside of that original cylinder, we put [a different material] ... and then we let the [manner 1 assembly] plop out, hinged from the bottom and just kind of plop outwards until they're almost 90 degrees. In fact, if you could have a little cable to kind of support it if you wanted to ..

3160:

3161: ZD: Exactly.

3162:

3163: MW: Now we're going to be radiating upward from what used to be the inside surface ... we didn't used to be using that inside surface ...

3164:

3165: HL: Yeah.

3166:

3167: MW: Now they radiate upwards ... we'll have . [insulation to minimize heat input to the ice]

Excerpt D-6 Episode 39, transcript paras. 3135-3167

The amount of detail and preparation evident in MW's description suggests his determination to convey his idea this time around, as does his reference to having prepared a PowerPoint slide. The proposal was immediately picked up and developed by ZD, HL and IE, working around a whiteboard, before instructions to the CAD operator to implement the horizontal disk radiator were finally given.

3526: ZD: We're actually doing this in real time MW. Sorry you can't see part of it.

3527:

3528: MW: Well I've got a little PowerPoint picture here which really looks bad ... I think you guys got the idea already. I'm really sorry I don't have the communications set up so I can watch you ... this sounds like a lot of fun.

3529:

3530: ZD: Yeah we really should make sure we can do that. Is there anybody there we can have the tech guys here talk to?

3531:

3532: MW: You know I could hang up for a moment. {inquires about technical support}

Excerpt D-7 Episode 39, transcript paras. 3526-3532

Upon seeing the updated CAD model displayed, HL and IE independently notice the possibility of an alternative means of deployment that involves folding the panels downward. All key participants express strong alignment with this as the best approach.

3558: HL: Well yeah, this thing could be [stowed] folded down, rather like this ... and then come up like that. [like familiar object 3].
3559:
3560: ZD: I don't think we have any problems whatsoever on this ...
3561:
3562: HL: No, no, this should work.
3563:
3564: ZD: That's why it's so important to see it.

{3 minutes elapse}

3624: IE: There's an interesting thing you could do, is… you could segment this and actually have it folded down... then when you have the guy wires go up to the top of the mantle you raise the mast.
3625:
3626: HL: It pulls the ...
3627:
3628: IE: It pulls the [assembly] up.
3629:
3630: HL: Yeah that's a good idea.
3631:
3632: ZD: That's the only, the best way to do it.
3633:
3634: IE: Yeah yeah.

Excerpt D-8 Episode 39, transcript paras. 3558-3564; 3624-3634

Landing Site Selection

When the team initially considered the issue[11], a northern landing site was suggested by the team leader ZD, based on a previous design study. However, early in the next session[12], information from a previous customer was relayed by the team leader, stating that northern polar landing sites would be inaccessible for both candidate launch windows under consideration. This was corroborated by another external expert reached by telephone later in the session.[13] The orbital geometries during the two launch windows appeared to heavily favour southern latitudes over northern ones.

387: EXT. EXPERT 1: Alright Earth to Mars ... 2011 ... How far up north do you want to go?

[11] S-040802 Episode 5 ~ transcript para. 1700
[12] S-041202 Episode 8 ~ transcript para. 380
[13] The term "external expert" was used to refer to members of the JPL technical community having specific expertise who could be called upon but who were not members of either the standing design team or the dedicated project team.

388:
389: ZD: I think we had 80.
390:
391: HL: 80-85 ... somewhere around there.
392:
393: ZD: 80 degrees N, 84 degrees W.
394:
395: HL: As long as we're on the icecap, we're okay.
...
399: ZD: We selected the landing site based on science input.
400:
401: EXT. EXPERT 1: Doesn't look like you can get there on a Type II.
402:
403: ZD: Yeah, that was the impression I got from [the previous study customer].
404:
405: EXT. EXPERT 1: On a Type I ... but it's going to cost you quite a bit.
406:
407: ZD: How much in <unintelligible> mass? Can you say something about that?
408:
409: EXT. EXPERT 1: Right on the ridge, so it's hard to say .. that's [a number].
410:
411: ZD: HY, can you find out how far down the polar ice cap extends?
412:
413: EXT. EXPERT 1: On the Type II, it looks like you're only going to be able to get up 55 and 60 N.
414:
415: HL: Ok, that's not good enough. Does that change if we launch in 2013?
...
421: EXT. EXPERT 1: It looks like it might actually get a bit worse in 2013.
422:
423: HL: Okay, well ... maybe we need to look at South Pole. That's too bad.

Excerpt D-9 Session 04-12-02 Episode 8 paras. 387-423.

The JPL internal customer HL expressed regret but initially accepted the notion of a southern polar landing site. However when further information came in by telephone confirming that the south polar ice probably consisted primarily of frozen carbon dioxide rather than water, HL expressed renewed desire to look more carefully at any possibility of landing in the north.

By the start of the next session[14], both ZD and HL reported having spoken with two knowledgeable sources who confirmed that 75-degrees north was the farthest northern latitude accessible on the basis of graphical solutions of the orbital equations known as "porkchops." While ZD seemed willing to accept this landing latitude and was inclined to

[14] S-041502 Episode 27 ~ transcript para. 480

move forward with the design, HL was more adamant that a landing site farther north would be required to assure the presence of the thick ice necessary for the mission to make sense.[15]

561: IE: One thing you might want to look at, if you want to get to the north pole, now right now if we do a Type II trajectory to the north pole we end up there at the beginning of northern fall.
562:
563: ZD: Well actually, we can't get there.
564:
565: IE: We can't get there?
566:
567: ZD: No.
568:
569: IE: On a Type II trajectory? ...
570:
571: ZD: Uh ... 2020 is basically when we can get there.
...
575: IE: 2020?? Really??!!
576:
577: ZD: Yeah.
578:
579: IE: Oh, the geometry is really nasty ..?!
580:
581: ZD: Yeah, it is.
582:
583: HL: Well now see, I don't think that that can possibly ... well I won't say can't possibly ...
...
607: HL: I don't know but we don't have a mission if we go to the south pole. The only way we have a mission is landing at the north pole.
608:
609: IE: We want water ice not dry ice?
610:
611: HL: We want water ice and we gotta land ON the ice.
612:
613: IE: Oh there is water ... but I mean ... the latest Odyssey pictures also indicate ..
614:
615: ZD: Water on the south ...
616:
617: IE: Water ice in the south region.
618:
619: HL: Yeah, but you're going to have to land almost RIGHT on the pole in the south, because it isn't very big and it disappears. I mean it's not going to do us any good if we don't <unintelligible>.
620:
621: ZD: Well maybe not ... because if you push (approach) the poles you are probably on a slopes filled with ice underneath the surface.
622:
623: HL: Yeah but, there's no point in sending a multi-year drilling mission if it's only a few meters deep. I mean, the benefit of this mission is going a kilometre deep into the polar cap.
624:
625: ZD: Sure.
626:

[15] S-041502 Episode 28

627: HL: And the only place you're going to do that is on the north pole ... in a deep ice part.

Excerpt D-10 Session 04-15-02 Episode 28 paras. 561-627.

HL continued, referring to a hard copy of a journal paper[16] showing a latitude of at least 84-degrees north would be required to find thick water ice—in a low region that could possibly once have been an ocean. ZD made repeated reference to graphical solution diagrams for trajectory equations known as "porkchops." He instructed a team member to retrieve and share the porkchops for the launch windows under consideration. (An

761: ZD: Yeah ... if you can unshare this, HY ... and if you then can OV share your stuff again ... and if you can find the porkchops DAP for 2011 ... Trajectory I, II. Are you all ready on that, OV?
762:
763: OV: Yeah, I worked it out here ...
...
769: ZD: Basically, it tells you that ... you know how to read those, right? IE?
770:
771: IE: Yeah.
772:
773: ZD: Basically it tells you that 2011 you only have negative DAP's, declination of arrival. And that means negative is south. And if it's south you really can not get to the north.
...
795: IE: I have porkchops for Type IV trajectories in here ... <unintelligible> seems to indicate that you can't do it.
796:
797: ZD: If you can't ... we really have a problem with the north.
798:
799: HL: I know, but if it means that we have to go 2020, I think that's a trade we ought to talk about, because I think that the cryobot mission means the north pole, and I don't see a way to do a cryobot mission in the south.

Excerpt D-11 Session 04-15-02 Episode 28 paras. 761-799.

At this point HL and ZD have staked out opposing positions: ZD insists on the basis of the porkchop trajectory graphs that high northern latitudes are inaccessible for both the 2011 and 2013 launch windows. HL maintains the mission only makes sense if it goes to the north pole. Both are armed with authoritative representations, bolstered by the opinions of external experts. HL suggests contacting another, particularly knowledgeable expert (a specialist in orbits and trajectories) in hopes of breaking the impasse.

Later in the session, when this expert enters the room he quickly confirmed the previous experts' readings of the trajectory graphs that indicate high northern latitudes to be

[16] Zuber et al., "Observations of the North Polar Region of Mars from the Mars Orbiter Laser Altimeter," *Science* 282 (Dec.11, 1998) 2053-2060.

inaccessible with ballistic trajectories.[17] However, unlike those consulted previously, this specialist has the expertise and access to more elaborate computer models to consider more complex trajectories. While others seemed to treat the trajectory graphs as definitive as to the possibility or impossibility of reaching certain latitudes, this expert used them more as *guides* for the applicability of relatively conventional trajectories. His attitude was similar to HL's, which was to say any latitude was *possible*, if the required fuel mass for a more complex trajectory could be accommodated.

1077: HL: According to the plots I've got, if you want to get kilometres of depth you need to get up to like 85.
1078:
1079: EXT. EXPERT 2: Okay.
...
1083: EXT. EXPERT 2: The alternative is a [complex] trajectory, where you're doing a deep space manoeuvre ...
1084:
1085: HL: We could do that.
1086:
1087: ZD: Sure. How much does that add <unintelligible> propellant? I mean we need to go deeper.
1088:
1089: IE: And that would be cheaper than going into orbit.
1090:
1091: EXT. EXPERT 2: I'd have to run an optimizer to find that out.
1092:
1093: ZD: Could you do that at some point?
1094:
1095: EXT. EXPERT 2: Yeah, maybe I could do that during this meeting or something.
...
1111: EXT. EXPERT 2: See now here 75 ... actually here's one that's 75 north. So there's a little region right there, so that implies to me that if you're up in here with a [mid-course manoeuvre] you could probably do it.
1112:
1113: ZD: With the [mid-course manoeuvre].
1114:
1115: IE: Yeah yeah yeah ... You still need it to get beyond ...
1116:
1117: ZD: Well can you get up to 85?
1118:
1119: IE: The [mid-course manoeuvre] ... you can get up ...
1120:
1121: EXT. EXPERT 2: You can ALWAYS get up to 85.
1122:
1123: ZD: Yeah, exactly ... with a [mid-course manoeuvre].
1124:
1125: EXT. EXPERT 2: Well it's just a matter of how much you're willing to pay.

Excerpt D-12 Session 04-15-2002 Episode 29 paras. 1077-1125.

[17] S-041502 E29 paras. 1025-1125.

APPENDIX E. ENHANCEMENTS TO NETWORK REPRESENTATION AND VISUALIZATION

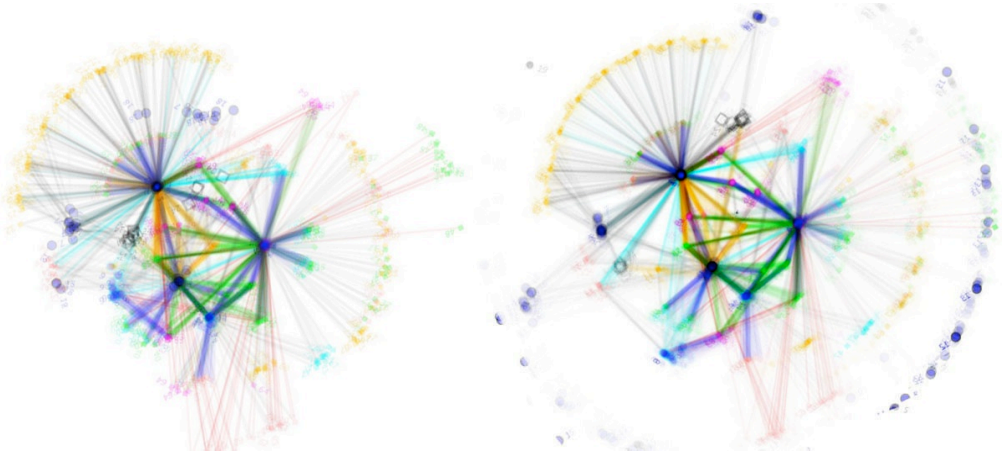
This appendix provides more detail on issues specific to network visualization, metrics and layout diagrams.

Stability of 2D Network Layout Diagrams

To assess the reliability of interpretation of relative node positions in 2D network layout diagrams, I undertook a series of studies of the stability of these layouts (how similar the end results were) with respect to randomized node starting coordinates. I ran full-episode cumulative layouts

Starting with Episode 7, I initially found stability to be very poor in that overlaying a series of layouts (allowing for mirroring, rotation and translation to obtain the best visual alignment) no consistent pattern resulted. However, I soon found that by making a few changes I could achieve dramatically improved stability. The first of these changes was to build up the layout by chaining successive network slices, rather than running the layout algorithm on the full network at once. The second change involved adjusting settings on the SoNIA program to eliminate a re-centring operation carried out between slices. (Though this was in principal nothing more than a simple translation, I assume it was introducing some error that was being systematically compounded from one slice to the next.)

Having made these changes, I was able to achieve dramatically improved layout stability for Episode 7. This gave me confidence that the relative node positions, at least of the most engaged actors, could be meaningfully interpreted in terms of alignment according to the spatial metaphor. I continued on to Episode 12, the results of which are presented below.



(a) without initial weak arcs (b) with initial weak arcs

Figure E-1 Episode 12 Stability Overlays with Weak Initial Arcs
69 nodes and 105 arcs (full episode cumulative aggregate built up progressively through 30 slices[18]). 20 runs superimposed, actors starting from points on a circle, discourse starting from random locations (a) without weak initial arcs between all actors; (b) with weak initial arcs between all actors. Weak arcs to constrain the initial positions of actors improve the overall stability of cumulative layouts, but add complexity to the arc database logic and are not conceptually consistent with the rest of the scheme

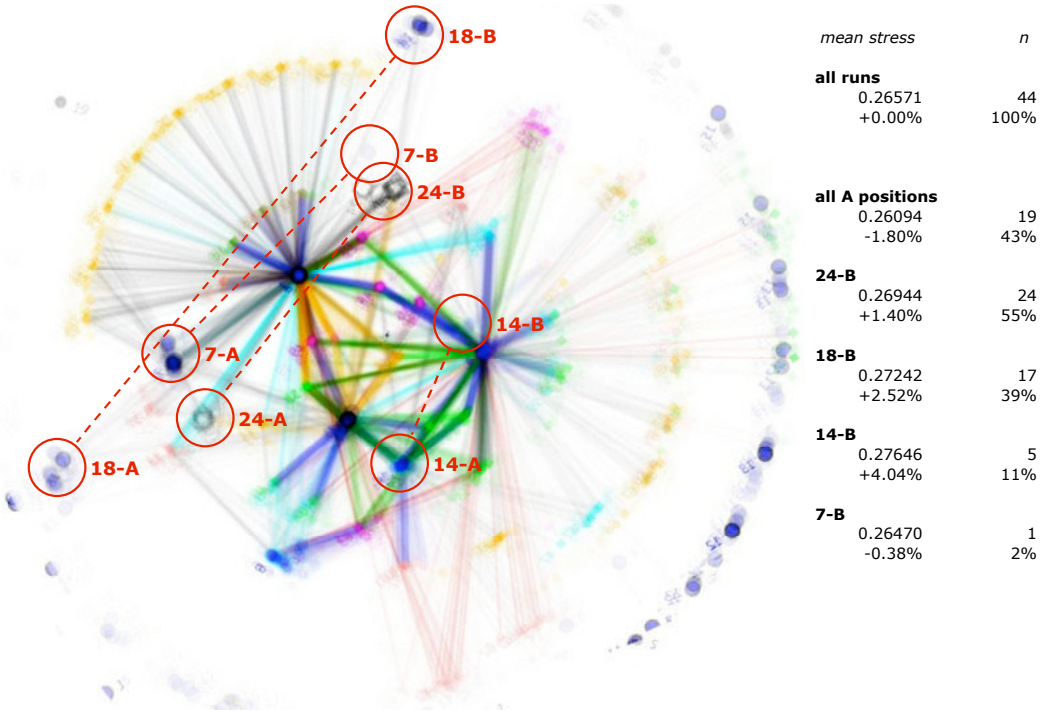


Figure E-2 Episode 12 Stability Overlays
This overlay is identical to (b) above, but highlights how some nodes assume "isomeric" positions, designated "A" or "B" in the diagram. In this case, the isomeric positions for node 14 were of greatest concern, since that node was the only more highly-engaged actor whose position was not stable. Also the two different positions would imply significantly different alignment between this actor and the others when interpreted according to the spatial metaphor. The figures to the right show that it would be possible in this case to differentiate between the isomeric positions of node 14 on the basis of increased mean stress in the networks showing this configuration.

[18] These tests were done before I adopted the approach of making slices correspond to 5-second time intervals. At the time these tests were done 30 slices constituted the entirety of Episode 12.

Excellent stability was achieved with Episode 12, with the single additional change of coding weak arcs between all actors to stabilize their initial positions with respect to each other. One relatively important actor node did appear to take two alternate positions which would have different interpretations according to the spatial metaphor. I borrowed the term "isomer" from chemistry, which refers to discrete alternate spatial configurations of substances with the same chemical formula. However, I found it was possible to differentiate between these isomeric positions on the basis of one having a consistently lower network stress, therefore representing a less distorted layout.

Having obtained an overall high level of stability on Episode 12, with the only apparently meaningful deviation from stability resolvable on the basis of network stress, I proceeded to Episode 39. The surprising result was, even employing all the techniques I had learned, I was not able to achieve anything like a stable layout for Episode 39!

Episode 39 is significantly longer than either Episodes 7 or 12. At the time I conducted these tests, Episode 39 comprised 81 nodes and over 400 arcs. So particularly in terms of the number of arcs, its cumulative network was considerably more complex. My first hypothesis was that this greater number of arcs might be related to the poorer result in terms of stability. To test this, I truncated the episode at a point when its arc database would have a number of nodes and arcs comparable to Episodes 7 and 12.[19] Again, to my surprise, this did not noticeably improve layout stability.

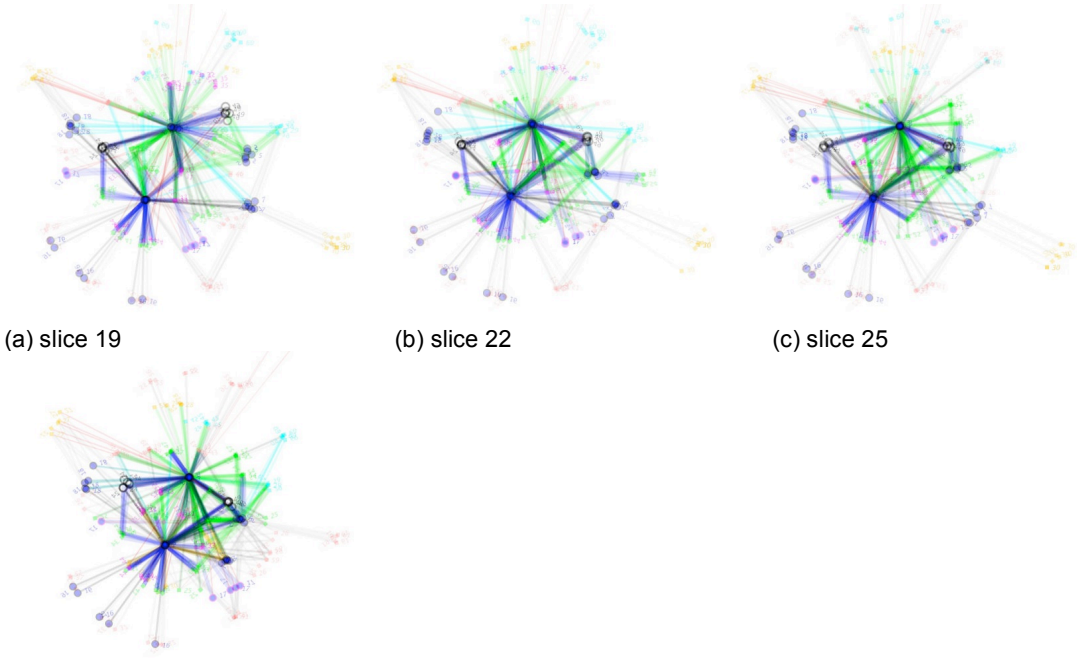
Testing stability at intermediate points prior to the point of truncation, I found that reasonably good stability appeared to persist up to a point and then to rather suddenly deteriorate.

[19] The point I chose was after slice 28 of a total of 66, when the network comprised 60 nodes and 173 arcs. At the time these tests were performed, I had not yet adopted real-time slices corresponding to uniform time increments, so these slice numbers are not comparable to those associated with later results.

(a) slice 19 (b) slice 22 (c) slice 25

Figure E-3 Deterioration of Stability in Progression of Episode 39
Overlays of 5 runs, evaluated at (a) slice 19, (b) slice 22, and (c) slice 25 of 28 slices. Stability appears to abruptly vanish between slices 19 and 22. The episode was truncated from an initial length of 66 slices to yield a network of comparable complexity to those for Episodes 7 and 12, from which quite good stability had been obtained. (Note that these slices are *not* the same as the real-time 5-second slices used to produce the final results reported in the main text.)

At this point I began to explore the possibility that a difference in the actual connectivity of the network was responsible for the sudden loss of stability. The most obvious change was the entrance of actor 5, participant IE, who had become highly engaged in working around the whiteboard by this time. Actor 4, participant MW on speakerphone, had been active early on but had been making very few contributions once discussion shifted to the whiteboard. As a test, I removed actor 4 and all related arcs from the database. The result was a significant improvement in stability:



(a) slice 19 (b) slice 22 (c) slice 25

(d) slice 32

Figure E-4 Improved Stability of Episode 39 Resulting from Removal of Actor 4
Overlays of 5 runs, evaluated as above at (a) slice 19, (b) slice 22, and (c) slice 25 of 28. Stability appears to have been restored by the removal of actor 4, who had become less involved with the more active participation of actor 5 between slices 19 and 22. To confirm that this was not simply a result of the removal of arcs associated with actor 4, I extended the episode to slice 32—a point when the number of arcs was again comparable. Relatively good stability was still obtained (d).

It is a mathematical fact that a graph of more than three points with fully-symmetrical connections (each point connected to all others by an arc of the same length) cannot be laid out graphically in two dimensions without differentially distorting the arc lengths.[20] In the cumulative networks I have been discussing, as several actors become highly engaged, and since arcs were aggregated on the basis of an *average*, the connections between actors tend to become symmetrical. To further test the possibility that the number of comparably highly-engaged actors in the network was be the principal difference resulting in the dramatically poorer stability of Episode 39, I independently ran test networks with increasing numbers of fully symmetrically connected nodes. The results were consistent with this explanation in that they showed significant departures from symmetry in 2D layouts became much more likely as the number of fully-connected nodes went from 5 to 6.[21]

[20] In general a symmetrical graph of more than n+1 nodes cannot be projected into n dimensions without distortion. So adopting a significantly more complex three dimensional network diagram only increases the number of distortion-free nodes to four!

[21] Stress appears in the network layout for more than three nodes; going from 6 to 7 nodes an asymmetrical layout becomes more probable than a symmetrical one.

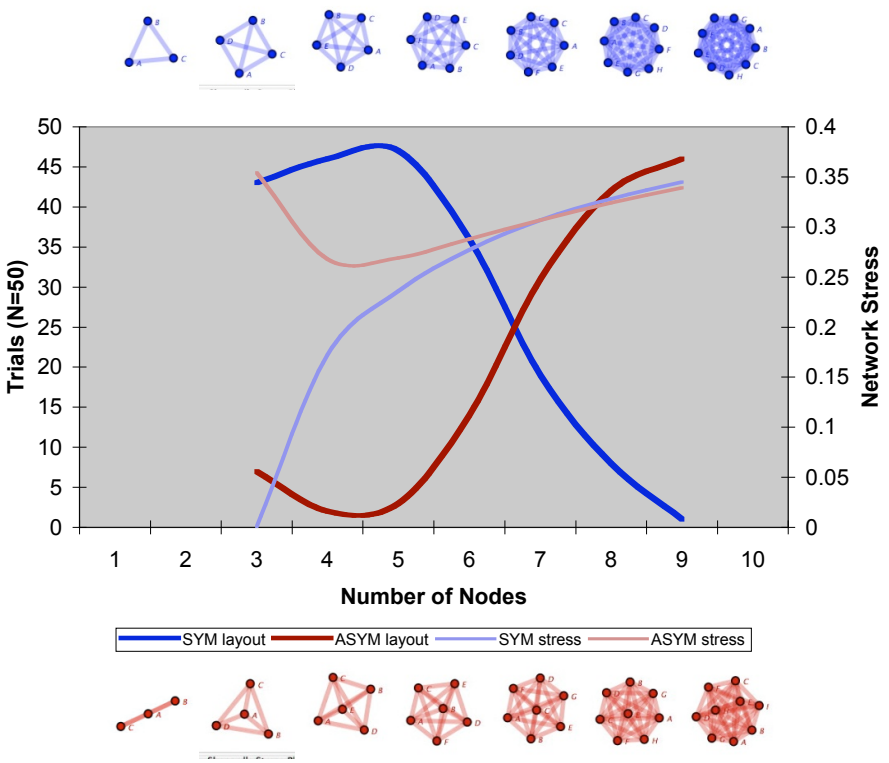


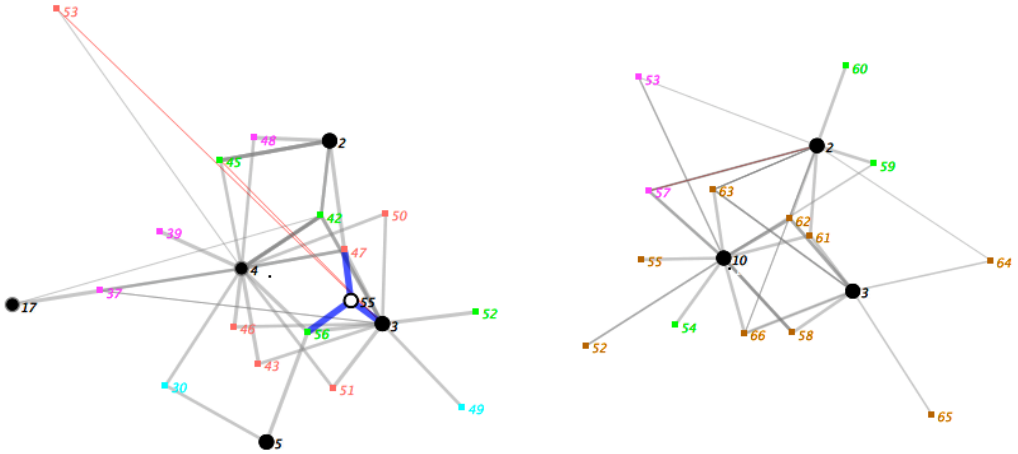
Figure E-5 Symmetry of Layout vs. Number of Fully-Connected Nodes
The likelihood that an asymmetrical 2D layout will result from a symmetrical, fully-connected graph increases significantly moving from 5 to 6 nodes, with asymmetry becoming more probable by 7. In this case, I use "asymmetry" to denote that the layout gives a misleading impression that one or two nodes have a different status or centrality than the others when they are in fact completely symmetrical in their connections. Note also that overall network stress is somewhat lower for symmetrical vs. asymmetrical layouts of 5 nodes, but that this difference vanishes by the time a graph contains 7 nodes.

At this point I felt it was sufficiently clear that the problems of layout stability were inevitable with more than three or four highly engaged actors (including representations). As a result I made various changes in the way I constructed and interpreted layout diagrams, and undertook an investigation into numerical structural metrics as discussed in the main text.

Mutual Engagement Metric based on Electrical Conductance Analogy

I have defined the conversational network property of mutual engagement as a reflection of the extent to which shared discourse nodes establish bridges between actors. I developed an overall network structural metric, discourse betweenness, as an index of this property, based on the conventional network metric of flow betweenness centrality. As discussed in Chapter 6, and elaborated in Appendix C, I found certain aspects of this metric to be problematic. Here, I offer a proposal for an alternative metric for mutual engagement based upon an analogy with electrical conductance, to be developed in further work.

To understand what this metric is intended to measure, compare two network slices in Figure E-6. These have been taken from the data to exemplify states of high and low mutual engagement:



(a) (b)

Figure E-6 Mutual Engagement: (a) High, (b) Low
Comparison of actor-discourse network configurations corresponding to situations of high and low mutual engagement. (a) Episode 39, slice 82; (b) Episode 21, slice 69.

In addition to the larger number of actors, there is a substantially greater number of direct bridges (two arcs via a shared discourse node) between actors in the slice exemplifying high mutual engagement. The arcs that constitute these bridges are also generally and uniformly strong. In the slice exemplifying weaker mutual engagement there are fewer bridges, and many of those that do exist show asymmetrical alignment (nodes with a strong arc from one actor tend to have a weak arc to the other). This pattern is characteristic of interaction wherein participants are systematically disagreeing over elements of shared discourse.

As an index of mutual engagement, the conductance of a network has several desirable properties. Applying such a metric would involve taking any pair of actor nodes and considering the set of all paths connecting them (directly and indirectly) as a network of electrical conductors.[22] Effective conductance increases with the number of paths and with the strength of the connections making up each path. Conversely, it *decreases* as the number of arcs in any path increases (assuming the arcs are of constant strength). Therefore, the number of shared discourse bridges and the strength of alignment would both have a direct, positive effect on a conductance metric; indirect paths (such as those through other

[22] Some readers may be more familiar with calculating the effective resistance of a configuration of parallel and series resistors. Because the coding scheme uses a similarity matrix (higher values indicating closer connection), arc strengths most naturally correspond to conductance. Resistance is the reciprocal of conductance, so the transformation is straightforward: parallel conductance behaves like serial resistance, and vice versa (as illustrated in Figure E-7).

actors) would contribute to a lesser extent owing to their greater length. Example conductance calculations and values for simple networks are illustrated in Figure E-7.

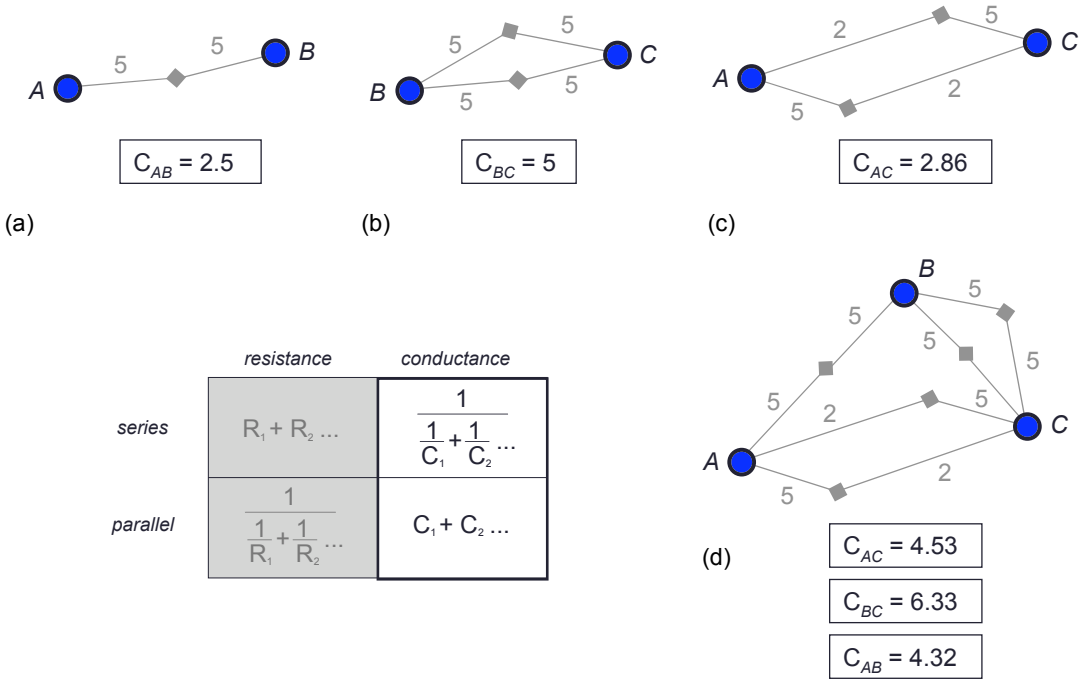


Figure E-7 (a-d) Effective Conductance of Single vs. Multiple Network Paths
Effective conductance would be helpful in discriminating between the high and low mutual engagement states shown in Figure E-6. Specifically, increasing the number of paths between actors increases the effective conductance (a & b), while weaker arcs in any path reduce the conductance of that path (b & c). Figure (d) is a superposition of (a), (b) and (c), illustrating how indirect paths (by way of other actors) increase effective conductance. (Representative arc strength values from the coding scheme correspond to strong support (5) and distancing statements (2).)

Characterizing a network as a whole would involve calculating the effective conductance between all combinations of actor nodes. The result would be a single-mode[23] matrix of actor nodes with values for the effective conductance between each node pair. Such a measure would differentiate between states of high and low mutual engagement portrayed in Figure E-6. The greater number of strong paths connecting actor nodes in Figure E-6(a) would result in a relatively high effective conductance between the principally-involved actors. In Figure E-6(b), the low connection strength of arcs in several of the bridging paths would lower the conductance of those paths (in the manner illustrated in Figure E-7(c)).

The computational effort required by more complex networks will put upper limits on the practical applicability of this metric. Because of the general utility of resistive network analysis, it is likely that existing, powerful algorithms can be adapted. To enable meaningful comparisons, it will also be necessary to identify an appropriate approach for

[23] A single-mode network is homogeneous, having nodes of only one type

normalization. As a start, we can follow the general approach taken by Freeman (1978) which is to compare the value for each node pair to a maximum value possible for a network of comparable size.[24]

Building on pair-wise closeness, we can assess several structural properties of interest. These include an index of centrality for particular nodes (both actors and discourse) and a measure of compactness or cohesiveness of the network as a whole. Following Freeman (1978), a straightforward index of compactness could be based on the average difference between each actor's closeness and the maximum value. As for centrality, actors could be ordered from most to least engaged simply by summing their closeness to all other actors (degree centrality of the single-mode conductance matrix). It would also be possible to assess cohesion and to resolve sub-clusters or cliques by applying these metrics to the single-mode conductance matrix.

It would also be possible to calculate the conductance between discourse nodes and all actors, to reflect the centrality or importance of particular discourse nodes. This would also yield a measure of the affinity of each actor for any particular issue or approach that came under discussion. Alternatively, this could be assessed by modelling current flow through the conductive network. (The most central discourse nodes would be those having the highest total current flow with potentials applied to the actor nodes in succession. This potential could be based on engagement as defined above, more simply on node degree or on a separate hypothetical attribute such as status.)

This notion of closeness also tends to mitigate the impact of some of the potentially problematic coding decisions discussed above—for example, in the coding of elaborations and collaborative products. This stems from the possibility of including semantic network relations directly between discourse elements. Whereas neither the flow betweenness nor the total degree metric take semantic network arcs into account, a conductance metric could use these relationships to moderate distances between actors (as shown in Figure E-8).[25]

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[24] The effective conductance for an actor-discourse network of two actors sharing a number (n) of discourse node bridges with individual arcs of maximum strength (c_{max}) is $n*c_{max}/2$.

[25] Doing so would not yield sensible results since, in both metrics, arcs are metaphorically treated as capacities or flows. In this regard, the conception of conductance seems to be more consistent with the meaning of proximity in the spatial metaphor.

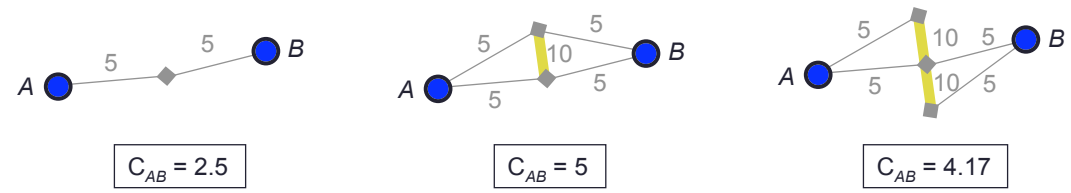

Figure E-8 Effect of Semantic Network on Effective Network Conductance
Semantic network arcs could moderate the effective conductance in cases of partially-overlapping engagement by several actors. Close linkage in the semantic network (c) yields an intermediate value compared to that obtained by considering only direct actor-discourse engagement (a & b).

As a result, deciding whether to code a contribution as a collaborative product, an elaboration or simply a related, follow-on idea (one sharing an image schema, for example) becomes a question of degree rather than a difference in kind.[26] No longer qualitatively different from semantic network relations, collaborative products simply create particularly tight clusters or bundles. The internal structure of these clusters could either be inspected or collapsed, depending on the scale of analysis.[27] This is a topic I address further in the main text, in terms of elaborations to the actor-discourse network conception of design activity.

Conversion to a Single Mode Network on the Basis of Pair-wise Closeness

Since the microanalysis I performed was relatively fine-grained, the most useful extensions are likely to be those that compress and reduce the level of detail in the networks, facilitating longer analytic time scales. The conductance metric presented above allows conversion of an actor-discourse network to one consisting only of actors (summarized below in Figure E-9).[28] This reduces the complexity of the network and allows direct comparison with the results of more conventional social network analyses. Such comparisons may be particularly useful in testing hypotheses that include constructs assessed by other methods.

[26] The selection of appropriate values for semantic network arcs (relative to the base scale for alignment) could be addressed empirically; alternatively, conductance could be compared with and without semantic network arcs.
[27] This is generally consistent with the actor-network theoretic concept of "punctualisation," in which distinct nodes form robust clusters, eventually operating as a single unit or a "black box" as far as the rest of the network is concerned.
[28] Remembering that actors can be either human participants or representations.

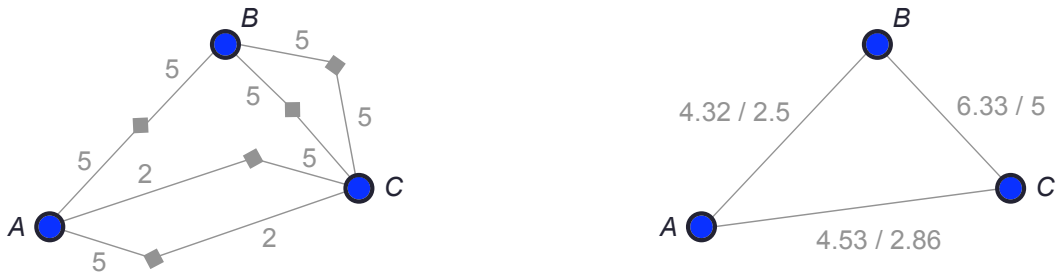

Figure E-9 Reduction of Actor-Discourse Network to an Actor-only Network
A simple example network from the previous section illustrates how the conductance metric can be used to reduce an actor-discourse network to a homogeneous (actor only) network, preserving meaningful network distances. Connections between actors by network paths through discourse nodes may be replaced by a single, direct arc. (Pairs of values for arc strength in the right-hand figure correspond to conductance with and without indirect paths, as shown in Figure E-7. Either approach can be taken; semantic network arcs may also be considered, as shown in Figure E-8.)

Other Technical Enhancements

Changes to Enhance Reliable Interpretation of 2D Layout Diagrams

Network layout diagrams are useful ways of conveying information about network structure in a compact and intuitive way. However, as discussed in Chapter 5, distortions of graph-theoretic network distances are inevitable in 2D (as well as 3D) layout diagrams of networks of this complexity. While the spatial metaphor (PROXIMITY=AFFINITY) serves as a general guide (i.e. in terms of overall clustering) these distortions can at times be misleading. Significance cannot always be attributed to the layout positions of actor nodes relative to each other.[29] This was one of the principal reasons metrics (e.g. total degree, flow betweenness) were explored, to understand the structure of networks in their full dimensionality apart from layout diagrams.

Network diagrams are most effective when they convey information in ways that take advantage of viewers' innate visual reasoning capacities (Larkin & Simon, 1987). Such things as the level of participation and the energy of interaction can be readily ascertained from the overall visual form and the degree of clustering evident in a diagram. A limited number of categorical distinctions may also be conveyed by colour and shape.

[29] Proximity of nodes in layout diagrams is most likely to be significant when the nodes are directly connected by arcs. When nodes are weakly connected their positions are more likely to "flip". In densely connected networks with near-uniform arc strengths, the precise relative positions become increasingly unstable as the number of (actor) nodes exceeds 5. ##See Appendix ## for details. Relative positions in episode cumulative aggregate diagrams are more reliable by virtue of aggregation by summing; compared to averaging this reduces the likelihood of several actors developing uniform connection strengths.

Conversely, the structural insight gleaned from network metrics is often not readily evident through visual inspection of diagrams alone. I found it useful to juxtapose graphs of metrics alongside the timeline for real-time networks and animations. It may also be helpful to reflect the values of structural metrics directly in static or dynamic layout diagrams by using a node attribute such as size. (So, for example, in a cumulative episode semantic network diagram, the size of a discourse node could reflect its betweenness centrality, making the relative significance of topics immediately obvious.)

To address potentially misleading variability in node positions, it may also be desirable to run a number of layouts in parallel (or in the background) with randomized node starting positions. An overlay could give some indication of the stability of nodes' relative positions. (Examples of this are shown above.) The results of a pair-wise closeness metric, such as also described above, could be used to further constrain the layout positions of sparsely-connected actor nodes.

With the current tools, the need to manually perform the iterative and recursive calculations required by these enhancements made them impractical for this research. Along with more automated and interactive support for coding, tools incorporating enhancements along these lines would be facilitate future work.

More Complex Logic for Arc Aggregation and Behaviour

Both real-time dynamic and cumulative aggregate network diagrams were useful to characterize interaction. As discussed above, multiple arcs are aggregated differently in the two cases: by average for real-time networks, and by sum for episode cumulative networks. In accord with the spatial metaphor, distancing statements are coded as arcs of low numerical strength. A problem exists in that such distancing statements cannot be handled consistently in both cases when different aggregation modes (sum vs. average) are used.

When aggregating by average, a distancing statement tends to lower the average compared to statements expressing stronger alignment—consistent with the effect of such statements in real time. When aggregating by sum however, a low numerical strength arc still *increases* the sum (albeit less than a strong arc would have). This can lead to contradictory behaviour. If an initially supportive actor decides subsequently to distance themselves from a discourse element, they nevertheless become *more closely* aligned in a cumulative layout than they would have been had they said nothing.

The opposite problem occurs for inscription. After an initial, strong inscription, subsequent weaker acts—such as gestural incorporation—continue to increase the sum (which seems

appropriate for a cumulative layout); they will however actually *lower* the average strength of the inscription in real-time. It does not seem appropriate for subsequent incorporation to have a weakening effect on inscription. A similar problem exists in the semantic network when actors' contributions are implicitly or explicitly at odds. The current approach is to code a zero-strength semantic arc, which has the desired effect of weakening the link for aggregation by averaging. Because such an arc has no effect on the sum, cumulative layout diagrams give no indication of contested semantic network relationships.

Together, these issues point more generally toward the need for a more complex arc aggregation logic for statements of certain types. (Summing and averaging are, after all, very simple operations in light of the complexity of human perception and cognition.) More theoretically-informed logics for arc behaviour should be based on further empirical work, in terms of participants' contributions and dimensions of representational "speech". As boundary conditions I propose the following:

- Distancing statements should weaken alignment in both real-time and cumulative networks.
- Inscription should remain constant or should monotonically increase with any subsequent positive engagement in both real-time and cumulative cases.
- An appropriate visual treatment is required for arcs corresponding to contested semantic network relationships.
- Duration of both inscription and semantic network arcs should be extended (at the appropriately-aggregated value) by subsequent acts involving the same nodes, rather than simply having the initial arcs "retire" after a fixed time.

These inconsistencies reflect a more general difficulty in the way negative or distancing statements are handled in a system which only permits positive numerical values. This, along with the limitations of arcs that "retire" after a fixed time, also pertains to the following technical development.

Minimizing Artefactual Movement in Animations

Animated network diagrams should make effective use of what is probably their most salient aspect, namely motion. At this point, rather than relating directly to events in the interaction, significant motion in the animations arises from the expiration of arcs. Because this depends upon an arbitrarily-chosen time interval, I consider it to be an artefact. Like the other enhancements discussed here, it is not possible to address this without significant programming and changes to the layout algorithm which are beyond the scope of this dissertation. Discussion of a possible solution is presented here for purposes of future work.

Artefactual movement results from sudden disappearance of arcs from the network at the end of their (arbitrarily fixed) duration. One way to address this would be to gradually reduce an arc's strength so as to approach zero at the point of expiration. While this might reduce artefactual movement, it has a strange and problematic implication in terms of the spatial metaphor: as long as weak arcs are used to denote negative or distancing statements, this would be tantamount to saying that strong statements of alignment necessarily become weaker (more distancing) over time. Since such an entailment is clearly nonsensical, I propose a different alternative.

There is a mechanical spring analogy at the heart of the layout algorithm (Kamada & Kawai, 1989). One way to address the problem of artefactual movement would be an elaboration of the analogy: decoupling the elasticity and length of arcs so that they are distinct parameters.[30] Length would continue to correspond to alignment in accord with the spatial metaphor. By making *elasticity* time dependent, an arc would be allowed to "retire gracefully," in that its effect on nodes' spatial positions would decrease compared to more recent arcs between the same nodes.[31] Despite becoming more elastic, distances between nodes would not change in the absence of new arcs. This would address the problem of artefactual movement while preserving the meaning of distance in the layout.

Such an approach is more complicated and would increase the information required to characterize each arc. It would, however, provide a possible alternate implementation for negative or distancing statements: as long, inelastic arcs. These would have a more decisive effect on layout diagrams than the current implementation of negative statements as low-strength arcs (i.e., long and very elastic arcs having little effect in the presence of other arcs.[32]

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[30] In engineering analysis, the stiffness of a mechanical element is a function both of its length and of the inherent elasticity of the material from which it is made.

[31] It is probably more convenient computationally to define a property of stiffness that approaches zero over time, as opposed to an elasticity that approaches infinity.

[32] It is important to note that this discussion pertains to layouts as two-dimensional diagrams of networks, not to the networks themselves as mathematical objects. Numerical metrics applied to networks in their full dimensionality are not affected by layout distortions. If distinct properties of elasticity and length were used for purposes of layouts, they would still need to be reduced to a single network distance value for the spatial metaphor to be meaningful. Though transients also exist in real-time metrics, it may only be useful to employ this notion of elasticity for real-time layout diagrams.