MODEL CONSTRUCTION AND TRANSFORMATION: A STUDY EXPLORING STUDENTS' CAUSAL EXPLANATIONS OF EVERYDAY PHENOMENA

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Contents

Summary

The central aim of this thesis is to explore students' diverse, dynamic and context-dependent approaches to causal explanations of everyday phenomena. As a result, a comprehensive framework, mutual transformation of situational models and causal models, has been built. The thesis illustrates the iterative process of learning environment design, data analysis, and progressive building of a comprehensive framework. The central contributions are: (1) a contextual, processual framework of causal explanations of everyday phenomena; (2) a multiple-space based, contextual model of problem solving; and (3) complementing and improving on research in model-based learning and causal explanations of everyday phenomena.

The framework proposed in this thesis involves several different categories and their relationships (Categories are the building blocks of our mental universe, and they provide the terms we think with, such as time and space). The categories are inducted from data and densely developed, thus they can be easily understood by students and practitioners and have the potential of informing educational practices. These categories are all formulated along the line of generic versus concrete with the concrete aspects structured by the generic aspects. Thus the framework has a high degree of logical coherence among these categories. Furthermore, it shows the dynamic process of both situational model and causal model building and how these models interact with and mutually transform each other in the process of causal explanation seeking.

The interaction and mutual transformation among different elements of the proposed framework are formulated in a problem solving framework as proposed by Newell and Simon (1972). Thus, it proposes several spaces interacting and mutually transforming each other, and in this way this study both inherits the basic vocabulary of Newell and Simon and makes improvements on it. Our framework extends Newell and Simon's proposal from one space to several spaces, and the interaction among these spaces makes the situation much more diverse and dynamic. Furthermore, while the original framework is symbolic, the current framework is conceptual and contextual utilizing local resources.

This study contributes to research in students' intuitive causal explanations and model-based learning in science education. Although these two fields explore two contrasting aspects (intuitive versus formal), current researches in them have some common characteristics: they remain at a general level and do not explore causal explanations or model building of a concrete phenomenon, so that there is no study on how local and contextual resources are utilized by students, and they do not explore the dynamic process of both model building and causal explanation seeking. On the contrary, this research explores students' dynamic and context-dependent behavior of building and transforming situational models and causal models to explain concrete phenomenon.

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1 Motivation and Theoretical Framework

1.1 Motivation

In the last two decades or so, a central inspiration in science education research is the widely established discovery of students' misconceptions or alternative conceptions about fundamental scientific principles despite many years of science learning, and this is the case even for MIT undergraduates (Disessa, 1993). Students' misconceptions in almost every scientific domain are carefully probed and documented, and various approaches and strategies to change students' alternative conceptions are proposed. However, it appears that the field of conceptual change is still in a pre-paradigmic stage, in the sense that none of these approaches can be regarded as a paradigm for the whole field. Finding out reasons and ways to improve it provides the motivation for this study.

1.1.1 Why science is so hard to learn: underlying reasons

The fact that such terms as misconceptions are not widespread in other educational fields suggests that difficulties faced by science educators seem unique. For example, in language education, at least the good students can grasp reading and writing skills relatively well and there are not many misconceptions. Schools and teachers are often blamed for their rote teaching methods, and the efficiency and effectiveness of learning in natural and everyday settings (such as apprenticeship; see Collins, Brown & Newman, 1989) inspire many researchers to design more naturalistic learning environments (Schauble and Glaser, 1996). But rote teaching methods are not the only factor at issue and the nature of science education must be examined to see where the difficulties lie. The examination identifies several factors that may contribute to the difficulties of science education:

- Evolutionally, science was not necessary for the survival and reproduction of human ancestors in the primitive age. Facing a hostile and precarious environment, our ancestors relied on quick response and functional knowledge (rather than a deep understanding of the inner mechanism of things and events in the environment) to cope with nature. Today, the human race has much more diverse goals to pursue, other than survival and reproduction, and various elaborate cultural forms (such as science) are created to achieve these goals. But biologically, human race today is not much different from its ancestors, given the relatively short time of civilization compared to the whole history of human evolution. So it appears that, unlike language learning, human beings are not endowed by nature to learn science with minimum effort.
- The application contexts of scientific knowledge, although expanding quickly, are still narrow and often restricted to formal and professional occasions. Put simply, unlike language, science is not an integral part of everyday life. It is true that people are using more and more science in everyday life, but they

normally only need to take advices from experts without understanding the underlying principles.

- Scientific knowledge and people's everyday knowledge are of a different character. Everyday knowledge is tacit, experiential and implicit – not available for introspection, while scientific knowledge is conceptual and explicit. Indeed, a lot of animals have the capacities of perception and motion, but certainly they do not have science. It might be said that perception and motion are embodied in biological capacities of the body, and it might even be an exaggeration to call them knowledge.

The above discussion suggests that the unnatural characteristics of science may be the reason for students' difficulties, leading to a vast gap between people's tacit and effortless beliefs and ways of living in everyday life and the explicit, systematic and effortful ways of scientific understanding. It is not a surprise that many well-educated adults today do not have a deep understanding of science, because what is important for them is to function effectively as culturally competent members in society, and this does not have much to do with understanding science. Scientific understanding is one of several ways of making sense of the world and often regarded as the greatest intellectual achievement of a human being, and it is this fundamental paradox between everyday understanding and scientific understanding that motivates us to find new ideas to solve this paradox.

1.2 Model-based learning as bridge

As stated above, a major difficulty in learning science is the gap between everyday understanding and scientific understanding, and model-based learning offers promise of bridging this gap. A model, such as a map or diagram, is a structural or functional analog of phenomena, objects and events in the world. In scientific research it serves to build a semantic relation between formal and abstract theory and phenomena, thus helping us build a rich, embodied understanding of theory (Giere, 1999, Gilbert & Boulter, 1998). "The practice of normal science depends on the ability, acquired from exemplars, to group objects and situations into similarity sets which are primitive in the sense that the grouping is done without an answer to the question, 'Similar with respect to what?'" (Kuhn, 1970) In other words, abstract concepts in themselves do not tell us how to apply them in different situations.

Model-based learning offers promise of bridging gap between scientific practice and students' everyday experiences. The gist of constructivist learning is to foster *authentic* learning experiences for the students, and here two notions of *authentic* learning in science education are identified: (1) Simulating the actual practice of the scientific community (Scardamalia & Bereiter, 1999). (2) Respecting and starting from students' everyday experiences, understanding and interest. Surely there is gap between scientific practice and students' everyday experiences, and model-based learning offers promise of bridging this gap.

As models are ubiquitous in scientific research, everyday life and classroom teaching, more and more science educators recognize a need for theories of both model-based learning and teaching. However, research in model-based learning is only in the infancy, and there is no coherent theory that outlines either the cognitive processes involved in model-based learning or how model-based teaching should be approached (Gobert & Buckley, 2000). Here the focus will be different kinds of models, and what kinds of models can best represent a subject domain or foster students' conceptual understanding of phenomena. There are various kinds of models, such as:

- Qualitative and quantitative models, with the former regarded as being able to capitalize on students' natural understanding and motivate their interests.

- Exploratory models and expressive models. They differ in the degree of freedom allowed by the learning environment. If a model is envisioned as a network of relationships between various entities relevant to a phenomenon, in exploratory models those entities are predefined so that students are left with the task of finding out relationships between them, while in expressive models these entities are specified by students themselves.

- Descriptive and explanatory models. Descriptive (or empirical) models are phenomenological models built from regularities of empirical data, while explanatory models propose invisible entities and relationships to explain and generate empirical regularities and observable behavior.

1.3 Objectives and contributions

The general objectives of this study are

- To provide a microgenetic, processual account of students' dynamic causal explanation seeking behavior.
- To understand the relative role in played by the general aspect and the concrete aspect of a certain context in causal explanation.
- To derive relevant implications for science education and open learning environments based on the current findings.

The major contribution of this study is a comprehensive framework of causal explanation of everyday phenomena. Current researches are at a high level of abstraction and do not pay enough attention to the dynamic processes involved in students' causal explanations and model building and role played by the concrete context in this process. On the contrary, this research specifically focuses on the contextual and processual/dynamic aspects of causal explanations and model building, thus complementing and contributing to research in this field. For conceptual change research, our research casts doubts on some of its basic assumptions and conclusions and offers new interpretations.

1.4 Theoretical Foundations

Science education is a multidisciplinary enterprise drawing theoretical inspirations from such diverse fields as science studies (philosophy, history, psychology and sociology of science), cognitive science, pedagogy, anthropology and sociology. In this research, constructivism and situated cognition are identified as the underlying theoretical foundations, which will be introduced respectively.

1.4.1 Constructivism

Constructivism is a movement sweeping almost the whole field of social sciences such as literature, arts and architecture, exerting a powerful influence on people's thinking and attitudes towards various issues of life, especially in western countries. In educational research and practice constructivism has gained much currency as a philosophy of knowledge and psychology of learning in the past two decades or so asserting that people construct their own knowledge and understanding of the world based on their past/current knowledge, experiences, values, goals, etc.

Constructivism is not a unified theory or approach. Rather, it can be regarded as a meta-theory uniting many different persuasions together, each carrying its own ontological and epistemological commitments. But a common thread can roughly be delineated running through all the persuasions of constructivism: a sense of both the power and limitations of the human race. An individual human being has certain "interpretative framework" or "point of view" to both enabling and constraining him to interpret and define life situations and respond to it. This interpretative framework is not inherent in nature, but is imposed on nature by human beings, thus human beings construct their own life experiences, and different people at different times or the same person at different times may construct different experiences and meanings from the same physical situation, and these experiences have different levels, notably biological, cognitive, and sociocultural levels. Cognitive level is higher than the biological level and sociocultural level is higher than both of them, and the higher the level, the more meaningful are the corresponding experiences.

The disputes between different versions of constructivism are often disputes between different ontological commitments. For example, there are disputes on whether social interaction or individual cognition should be regarded as primary. Theoretically, the disputes are hard to solve and it is beyond the scope of this thesis. As educational research is an applied science, a practical and pluralistic approach is appropriate. Different versions of constructivism can be regarded as representing different levels of analysis and complementing each other, and upper-level analysis can take lower-level analysis for granted, just as physics, chemistry and biology represent different levels of analysis and complement each other.

Different versions of constructivism can also be divided into two strands: those concerned with cognitive aspects of knowledge and learning (that is, cognition and representation in the head, or we might say knowledge and learning in the traditional sense), and those concerned with social and cultural aspects of knowledge. Cognition and representation in the head are not self-contained but an integral part of people's everyday life and activities, which always happen in a larger social and cultural context. Thus, social constructivism reformulates knowledge and learning as community of practice, identity building, and peripheral legitimate participation. These sociocultural categories are regarded as fundamental and generative of traditional mental and cognitive constructs such as mental structures and schemata, and become the focus of research.

1.4.2 Situated Cognition

Whereas some versions of constructivism, such as cognitive constructivism, are evidently dualistic and individualistic pitting individuals against outer natural and social world, all versions of situated cognition (Clancey 1997, Lave and Wenger 1991) claim to overcome Cartesian dualism and unite individual, nature and social world into a holistic whole. The key terms are "dialectic" and "system": agent, nature and society are regarded as different elements in an organic system. They are defined not substantially but relationally by the dialectic relationships between them. They not only interact with each other but more importantly, they co-define, co-determine and co-constitute each other and no element is self-contained. In other words, there are structural coupling between agent and his physical and social environment.

For educational research, situated cognition construe knowledge and learning not as isolated and self-sufficient, but inextricably linked to the context and activity in which learning happens. Knowledge and learning in this construal are not residing in the agent's head or the environment, but residing in the dialectic relationship between agent and the learning context:

"The activity in which knowledge is developed and deployed, it is argued, is not separable from or ancillary to learning and cognition. Nor is it neutral. Rather, it is an integral part of what is learned. Situations might be said to co-produce knowledge through activity. Learning and cognition, it is now possible to argue, are fundamentally situated…. A concept, for example, will continually evolve with each new occasion of use, because new situations, negotiations, and activities inevitably recast it in a new, more densely textured form….This would also appear to be true of apparently well-defined, abstract technical concepts. Even these are not wholly definable and defy categorical description; part of their meaning is always inherited from the context of use." (Brown, Collins & Duguid, 1989).

There are two levels of structural couplings between agent and environment: neural and social (Roschelle & Clancey, 1992). At the social level, knowledge is construed not in the traditional terms of representation and cognition but embodied in people's activities, practices and social relationships. The focus is not what people know, but what they do. Certainly there are also knowledge and learning in the traditional sense, but they are seen as derivative of social practice and activities, not explanatory and important in themselves. At the neural level, the recent paradigm change in cognitive science from discrete symbolic models to analog and embodied models of knowledge (Clancey, 1997) may help us better understand structural coupling at this level. Embodied knowledge is experiential, tacit knowledge not separated from our biological body, but in virtue of our having such a body and our contact with the world (Dreyfus, 1992).

1.5 Structure of Dissertation

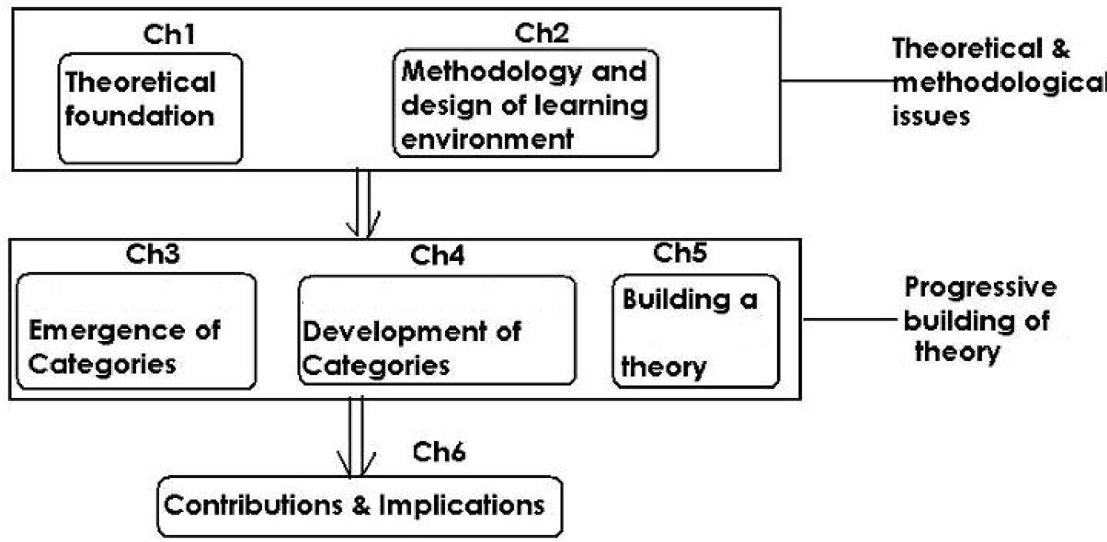

Figure 1-1: Structure of the dissertation

The structure of this thesis is quite straightforward, as shown in Figure above. The first two chapters discuss theoretical and methodological issues, with the first chapter introducing theoretical foundations of the thesis and chapter two illustrating the iterative process of learning environment design, data analysis and methodologies adopted. Chapter three, four and five build a comprehensive framework in a progressive manner. Chapter three documents the first stage: open coding and the inductive emergence of various categories from empirical data. Chapter four illustrates the development and saturation of current categories, and the discovery of new categories and formulation of these categories along the line of the generic versus concrete, thus giving a degree of logical coherence among the various categories. Chapter five builds on work of Chapter three and four to formulate a conceptual framework of causal explanation of everyday phenomena. Chapter six discusses the contributions and implications of this study.

1.6 Conclusion

The theoretical framework in this chapter provides inspirations for design of the learning environments, but they are of a high level and philosophical character, so in themselves they are not able to provide detailed design principles, and more specific theories are needed for this task. In the spirit of seeking more specific theories for system design, the next chapter provides lower-level theories as design principles and illustrates the learning environment in detail.

2 Design of the learning environment

Faithful to the constructivist doctrine of learning by doing, educational research itself can be viewed as an iterative and long time process of learning by doing. Specifically, this research is initially framed as a qualitative study researching students' learning experiences in an inquiry-based, interactive learning environment. Moreover, a bottom-up, process-oriented and micro-genetic methodology is adopted to understand in detail students' diverse learning experiences, and video analysis provides the suitable technology for this purpose with its ability to capture students' activities in enough detail. Nonetheless, there are some inherent difficulties in doing this kind of research, and this chapter tries to draw some lessons from the learning experiences. The following sections illustrate the iterative process of this research, the problems met, and how the research is reformulated to solve the problems. The process is iterative in several senses: design of the learning environment is iterative, the final product is formed in an iterative process, and there is an iterative relationship between product of analysis (that is, the framework proposed in this research) and design of the environment. The research process will be divided into three stages: the initial design and analysis of the learning environment, reflection on the problems met, and how the research is reformulated to solve the problems. Hopefully this may be of some help to other researchers of the same persuasion.

2.1 Initial design of the learning environment

Although here it is called "initial design", the design actually is quite complex. It aims to implement model-based learning by engaging students in building various models of everyday phenomena (here the phenomena of falling objects) in an inquiry-based, computer-mediated learning environment, as model-based learning is seen as possessing potentials to bridge the gap between abstract theories and diverse phenomena, and between students' interests, capacities and scientific ways of thinking.

The phenomenon under study is falling objects and air resistance. In general, students should be able to both describe the phenomenon ("what is the case") and use explanatory principles to explain the phenomenon ("why is the case"). Furthermore, they should also be able to grasp both the static aspects and the dynamic aspects of phenomenon and event. Thus, students should be able to

- Build both process models and causal models of the phenomena. This corresponds to descriptions of the phenomena.
- Use explanatory theories (Newton's laws) to explain these models: to explain local change in process models and global patterns in causal models (Liu & Chee, 2003). This corresponds to explanations of the phenomena.

2.1.1 Experimental design of Original Study

The table below summarizes the time allocation and constituent elements of the learning environment in different sessions. There are three sessions in this study, each being an independent and continuous time unit and with a specific goal. The idea is to provide closure for each session so that students can have independent achievements in each session.

Session	Content and goal	Form
Session One	Interview	Individual, paper-based
	Explain phenomena (Build expressive models implicitly)	Peer, computer based (System One)
	Build process models	Peer, computer based (System One)
Session Two	Build causal models	Peer, computer based (System Two)
Session Three	Use particulate model to explain air resistance	Peer, paper-based
	Discussion of previous interview	Peer, paper-based

Table 2-1: Sessions and contents of the initial learning environment

To facilitate subject interest and engage fruitful discussion, it is decided that peer collaboration will be used as the form of this empirical study. This research does not intend to teach subjects physics from afresh, so subjects who have majored in physics before are chosen. As there are no collaboration tools in the learning environment, subjects who are good friends and have worked together before to facilitate collaboration are chosen. Another reason is that subjects feel more comfortable working with friends instead of a stranger. Table 2-2 (S4 for Secondary 4; score is result for preliminary A level physics test; names are pseudo names; Group One has only participated in session 1) presents basic information of subjects in each group.

Their backgrounds are quite similar: all are 16 years old, having finished Secondary Four and now waiting to enter Junior College, and scored relatively well in preliminary A level physics test.

Group	Subject One					Subject Two				
	Name	Sex	Score	Age	Grade	Name	Sex	Score	age	Grade
One	Dennis	F	A1	16	S4	Lo	F	A1	16	S4
Two	Nicole	M	A2	16	S4	Gary	M	A1	16	S4
Three	Ken	M	A1	16	S4	Tian	M	A1	16	S4
Four	Andy	M	A1	16	S4	Jason	M	B4	16	S4

Table 2-2: basic information of subjects in initial study

2.2 Problems faced

The design illustrated above is quite complex, and after trying it out in several groups of subjects (including pilots) and analyzing the result, several difficulties are met, including both theoretical and practical difficulties. The biggest difficulty is: is this a confirmatory or exploratory study? The nature of the study indicates that it should be both. Much effort has gone into design of the environment and claims are made for the effectiveness of the design, so naturally these claims should be confirmed. But even if it is confirmed, theoretically it seems not very interesting to just confirm one's conclusion. The more interesting issue should be what students do in the learning environments, which means that result of the analysis should be something different from the proposed design principles. Students' model building behavior can be grouped into two patterns:

- Some students can correctly build and reason with the models with scientific principles, and this shows the effectiveness and structuring role of the computer-based cognitive tools. But this does not mean that these students have eradicated their misconceptions, since scientific understandings and misconceptions often coexist, and being able to understand and use scientific principles does not mean having examined and eradicated misconceptions. In other words, scientific understandings are compartmentalized.
- Students have met various difficulties and make various mistakes in the model building process, but how they deal with difficulties and mistakes is very much depending on individual characteristics of students since the environment has not enough structure for fostering discussions. Some have engaged in hot discussions and there is evidence to show that they have improved their understanding of the scientific principles, but some just try to finish the task as soon as possible and ignore the requirement to reflect on and possibly eradiate mistakes. Thus, one possibility is to implement more structures for the correction of mistakes. But it is hard for the system to be specific about the nature of the mistakes instead of just providing general guidelines (as past research in intelligent tutoring systems shows), and even if this is done, it does not look like an interactive learning environment but more like an agent.

Facing these problems and in search for a solution, basically there are three choices available: a confirmatory approach, an exploratory approach, and a combined approach, each with its own difficulties:

- For the confirmatory approach, the performance is different from subject to subject, but at least most of them can engage in the work of model building and the idea of process models and causal models are very natural for them to understand. The models can also reveal students' mistakes and conceptual confusions, but whether the subjects have actually reflected on their mistakes and possible eliminated these mistakes is very much depending on the particular qualities of the individuals themselves, so the result is not very generalizable.
- For the exploratory approach, there is a problem of the nature of the result of the analysis. The data show that students do demonstrate diverse and interesting behavior in the learning process, but to build a coherent theory or conceptual framework from the messy data remains a challenge. A theory should be dense and coherent, with many different patterns closely related to each other and organized in a tight structure. All kinds of patterns from the data can be discovered, such as what kind of mistakes subjects make and what reasoning patterns they are engaging in, but it seems hard to unify them into a tight theory.
- For the combined approach, the situation becomes very complex: in what sense it is confirmatory, in what sense it is exploratory, and how are they combined?

All three approaches seem untenable. Unexpectedly, the hope of building a unified framework comes from the part that has received least attention in the study: engaging students in phenomena explanation. It is only a part of Session one (see Table 2-1), and the initial purpose is just to warm up students for later model building activities by introducing students to various phenomena related to air resistance. But students demonstrate a degree of ingenuity and spontaneity which is quite remarkable, and more importantly, there is a high degree of coherence and density in the data in this part which is not seen in later model building activities. So an important decision is made to actually abandon other parts and strengthen and concentrate on the part of phenomena explanation. Students are no longer explicitly asked to build and reason with models, but they are still building and reasoning with mental models implicitly to explain phenomena, so the former work is not entirely abandoned, but the research focus has changed:

- If students are not asked to build models, session two and three (building process model and building causal model, see Table 2-1) model building are no longer needed. It is just because our purpose is theoretical and conceptual articulation and these sessions seem not very promising for achieving this purpose.
- The confirmatory approach is abandoned and now the approach is entirely exploratory, so that in redesigning the learning environment the focus is not on the effectiveness of the design but on consolidating and building on the current categories and theoretical framework.

2.3 Reformulation of study

The above description leads to a quite radical reformulation of the study in three stages:

- The first stage is the open coding stage in which data are coded from all perspectives, with categories emerging and inducted from empirical data. The current work as described above constitutes the first stage.
- In the second stage, there are mainly two tasks:
  - Use the emergent categories as coding scheme to develop and saturate current categories.
  - Based on current theoretical concerns, develop new instruments, test them on subjects, and discover new categories and properties.
- In the third stage which is the final stage, coding weaves the fractured data back again and conceptualizes how the emergent categories relate to each other.

2.3.1 Experimental design of the New Study

At first, Table 2-3 presents subjects' basic information (Score is based on recent school exams and names are pseudo names). Subjects in each group are friends who have volunteered for the study. Their backgrounds are quite similar: all are roughly

18 years old pre-matriculation students from mainland China under the auspices of the Ministry of Education of Singapore (and they are normally referred to as the SM2 batch). Since they are chosen from good students of the best universities in China, they can be regarded as the top 5 percent students in China. To differentiate them from subjects in the original study, they will be denoted by two letters (such as *SA*) while the Singapore subjects will be denoted by one letter (such as *L*).

Group	Subject One					Subject Two				
	Name	Sex	Score	Age	Grade	Name	Sex	Score	Age	Grade
One	SA	F	A1	18	SM2	FA	F	A1	18	SM2
Two	TB	M	A1	18	SM2	SB	M	A1	18	SM2
Three	GB	M	A1	18	SM2	AB	M	A1	18	SM2
Four	BG	M	A1	18	SM2	SG	M	A1	18	SM2
Five	LG	F	A1	18	SM2	FG	F	A1	18	SM2

Table 2-3: basic information of subjects

In the new study, there is only one session lasting from one and a half hour to two hours (see Table below). The session consists of three phases: a briefing, an interview between the researcher and each of the participant, and peer discussion. In both peer discussion and interview the questions are presented to them in paper form (See Appendix IV), but in the interview the researcher will ask additional questions to probe students' understanding deeper when the opportunity arises. Although interview and peer discussion are paper based, subjects are not required to write their answers down as in an exam. Writing tends to interrupt the process of fluid discussion, and as long as they can articulate their minds, their answers can be retrieved from the transcripts, so in this study subjects are not asked to write down their answers.

Session	Content and goal	Form	Time
Session One (Total about 1.5 to 2 hours)	Briefing	Peer informed by researcher together	20 min.
	Interview	Individual, paper-based	10-20 min.
	Explain phenomena	Peer, paper-based	60-90 min.

Table 2-4: Sessions and contents of the new learning environment

In briefing, there are quite a few things to brief the subjects since they, being from China, may have difficulty in engaging in serious and long time discussions in English, as students in China normally use English only in the school, and even in the school, it is mostly used in the English class only:

- Informing them about the purpose and objective of the study;
- Familiarize them with the video-recording settings;
- Informing them about the proper manner of engaging in discussion, such as "raise your voice", "respect your partner but also speak out your own ideas", "support your claim with argument and evidence", etc.
- To warm them up for discussion in English, asking each of them to speak out for about five minutes on a familiar topic, such as their home town.

The interview is structured, and the researcher mainly asks the students to clarify various issues and correct factual errors without providing clues and answers to them. Basically it is to attack the loopholes in their answers and asks for clarification. For example, if a student says that all objects fall at the same speed in the air, a question is asked "Are you sure? I give you a coin, and a pen, they will fall at same time?"

In peer discussion, students are asked to go through the questions one by one. The researcher's role is to provide logistical help in various places:

- Some of the situations presented to subjects are impractical for them to do experiments in the laboratory, such as falling of two iron balls (one has larger diameter), and subjects tend to give the wrong answer. In such a case, the researcher will see the direction of their discussion, provide the right answer and ask them to explain if they stray away too far from the right answer.
- Providing facts, such as the formula for the volume and surface area of a sphere in terms of its radius.
- If the researcher sees that they have skipped a question and are not proceeding as planned, they will be asked to return to the omitted question.

2.4 Conclusions

Having illustrated design of the environment, the following chapters embark on the journey of data analysis, with Chapter 3, 4 and 5 dealing with the three stages of framework building respectively.

3 Open Coding and the Emergence of Categories

This chapter illustrates the emergence of inductive concepts and categories in the process of open coding of empirical data, which is the first stage of framework building. The data come from the initial experimental study (see section 2.1.1) in which four groups of Singapore subjects engage in collaborative inquiry of explaining falling phenomena. Open coding means coding the data from all perspectives without preconceived ideas or coding schemes, and this requires an open mind to novelties. Note that in the following chapters, a category will be in bold letters and the first letter will be capitalized (**Effect Combination Strategies,** for example), and when a category appears in a heading (thus it is impossible to use bold letters to differentiate it from other words), it will be in bold and italic letters (***Effect Combination Strategies,*** for example).

3.1 The Effect Combination Strategies Category

In Chapter Two, two situations (falling of Elephant and feather, and two Styrofoam with one's surface area twice of the other) are designed to create puzzles in the subjects. Indeed this is the case and many ingenious solutions are invented by subjects to solve their puzzles. See the following excerpt for a short discussion between two subjects to predict and explain which of the two Styrofoam fall faster and why (L and D are Initial letters of the pseudo names for subjects):

D	I think it will be the same. Maybe they will cancel out each other.
L	I don't know...I think the larger one will fall slower.
	Experiment: both fall at the same time.
L	Yeah, it is the same, because they cancel out each other. It has greater weight, but it also has greater resistance, so it roughly cancels out.

Here D and L use the idea of "cancel out" to explain why both objects fall at same time although the larger one has larger resistance (thus causing it to fall slower), that is, "canceling out" of two tendencies is used to explain the final result. Here *Tendency* is defined as a specific factor's relative effect on the outcome when comparing two situations, which may be different from this factor's absolute effect on the outcome. For example, the absolute effect of resistance on falling speed is always negative since increase of resistance causes decrease of speed, but the relative effect of resistance can be positive, negative or naught (which means there is no effect) depending on the relative value of resistance in two situations. Thus, if an object has less resistance than another, it will fall faster, and the relative effect is positive. Table 3-1 summarizes how the relative effect changes with the absolute effect and the comparison between two situations. The factor F has value F1 and F2 in two situations, and its absolute effect on the outcome is listed in the first row.

	(Absolute effect) Positive	(Absolute effect) Negative
F1>F2	Positive	Negative
F1<F2	Negative	Positive
F1=F2	Naught	Naught

Table 3-1: Relative effect as interaction of absolute effect and comparison of situations

Subjects have utilized many of the strategies as summarized in the table above in different situations, as demonstrated by the empirical data:

- When one tendency is naught, the situation becomes simple. Thus, for two falling objects of the same resistance, the one with larger weight falls faster. For objects of the same weight, object with larger resistance falls slower. For example, in the case of iron ball and wooden ball, K explains "Why the iron ball falls faster? Because it is heavier, right, (it has) greater mass".
- When no tendency is naught, from Table 3-1 it is easy to see that the two tendencies may be of the same direction (that is, both are positive or negative) or be in conflict with each other (that is, one positive and one negative). The former case happens when one object has larger weight and less resistance than the other. In the latter case, the relative strengths of the opposing tendencies are compared and the tendency with larger strength overcomes the tendency of smaller strength.
- The subjects may just focus on the salient tendency and ignore the other tendency, thus get incorrect result, since that tendency is not naught and can not be ignored. The rules are: object with larger weight falls faster or object with larger resistance falls slower. This ignorance may happen when subjects' attention is unduly attracted by the salient tendency.

Thus these various strategies can be grouped in a schema called **Indirect Effect Combination Strategies** aiming to determine the total effect of different tendencies, and it is called *Indirect* to denote that the effect is relative and indirect. The schema has the following dimensions:

- **Ignoring Naught Tendency**. This happens when one tendency is naught and it can be ignored.
- **Focusing on Salient Tendency**. This happens when subjects may be unduly attracted by one salient tendency and incorrectly ignore the other non-naught tendency.
- **Indirect Overcome**. This happens when two tendencies are in conflict, and tendency with larger strength overcomes the other tendency. It is called indirect since tendency denotes indirect effect.
- **Indirect Balance**, which is a special case of **Indirect Overcome.** This happens when the two opposing tendencies are of the same strength.

After the emergence of the category **Indirect Effect Combination** as discussed above, it is natural to extrapolate and propose another Category **Direct Effect Combination Strategies** for combining the effect of different factors on the outcome directly without comparing two situations. Whereas in the Category **Indirect Effect Combination Strategies** the ways of combination are quite limited, in the Category **Direct Effect Combination Strategies** there are many different types of combination. For example, the rule for combining forces in mechanics is vector addiction, and in balance beam the rule for combining effect of torsion caused by weight and length is *weight multiply Length*. In the case of falling, the two factors (weight and resistance) are opposing each other and one possibility to combine their effect directly is *weight* *minus resistance*, which can be called **Direct Overcome** to contrast it with **Indirect Overcome**. A special case of **Direct Overcome** is **Direct Balance** (to contrast it with **Indirect Balance),** which happens when weight and resistance are the same so they balance each other out.

Both **Direct Effect Combination Strategies** and **Indirect Effect Combination Strategies** are demonstrated and inducted from in subjects' work. By combining these two categories together, the Category **Effect Combination strategies** is obtained, and the following figure shows its various subcategories. Numbers are used to denote the hierarchical relationship between different categories. Thus, **Direct Balance** is a subcategory of **Direct Overcome**.

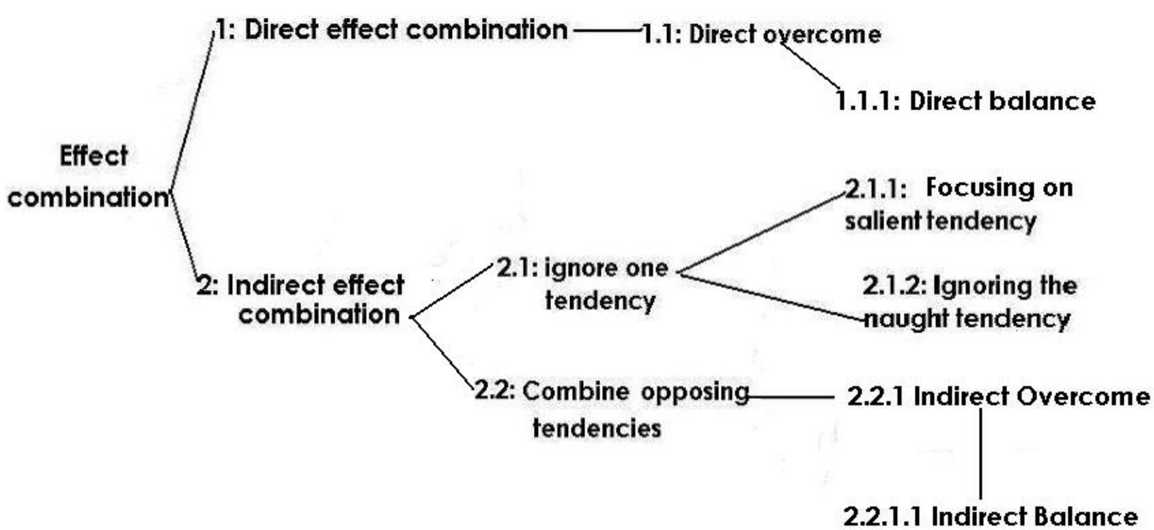

Figure 3-1: Structure of the Category *Effect Combination Strategies*

The specific rule subjects use to explain in a certain situation is defined as the Category **Causal Rule**. Thus, causal rule is the result of applying **Effect**

Combination strategies to a certain context. Note that this is an initial formulation and will be improved in later sections as the framework develops.

Figure 3-2: Relationship between Context, Effect Combination Strategies and Causal Rule

Here a causal rule is defined as a one-dimensional single variable combining the effect of different factors or dimensions of the situation. In the case of falling, the two factors are weight and resistance, and a causal rule would be something like "Object with larger value of Weight minus Resistance falls faster". The table below shows the correspondence between different strategies and causal rules.

Strategies	**Causal rules**
S1.1: Direct overcome	R1: Object with larger value of Weight minus Resistance falls faster
S2.1.1: Focusing on salient tendency	R2: Object with larger weight falls faster
	R3: Object with larger resistance (or surface area) falls slower
S2.1.2: Ignoring naught tendency	R4: For objects of same resistance, the one with larger weight falls faster
	R5: For objects of same weight, the one with larger resistance falls slower
S2.2.1: Indirect overcome	R6: The object with much larger weight and larger resistance falls faster

	R7: The object with much larger resistance and larger weight falls slower
S2.2.1.1: Indirect balance	R8: If one object has larger weight and larger resistance, they may have the same speed

Table 3-2: Strategies and corresponding Causal Rules (S: strategy; R: rule)

Together, the different subcategories of **Effect combination strategies** constitute a relatively complete characterization of subjects' problem solving strategies to combine effects of different factors (here weight and resistance). Basically there are two ways to get the total effect. One (Direct Effect Combination) is to directly combine the different effects, normally in the form of a formulae, such as weight multiply distance in the case of balance beam. Another approach (Indirect Effect Combination) is to compare the strength of different factors' relative effect on the outcome.

3.2 Categories *of Approaches & Problem Conceptualizations*

The first step in problem solving is to conceptualize the situation, and in physics problem solving, it is widely acknowledged that students' conceptualizations of the Situations are influenced by higher order reasoning patterns or approaches. The following sections illustrate these two categories (high-order Approaches and corresponding problem conceptualizations) in detail.

3.2.1 The formal and symbolic approach

In a formal and symbolic approach, students regard equations as meaningless symbolic manipulations and problem solving as finding the right equations that contain variables that appear in the problem statement or outcome (Larkin, et. al., 1980), thus they adopt a backward reasoning process. This approach is necessarily quantitative, but it can have two forms: numbers or variables. Nonetheless, no instance of this approach is found, the reason perhaps being that the subjects in this study are not so bad at physics. Observing the principle of sticking to the data, this approach is not included in the framework. Accordingly, there are no illustrations of problem conceptualizations based on this approach.

3.2.2 The formal & conceptual approach

The formal and conceptual approach is the approach normally presented in textbooks. Students adopting this approach regard symbols as representing scientific concepts and principles (force and Newton's laws, for example), but these concepts and principles are of a formal character as presented in a textbook (Larkin, 1983). They can use these concepts and principles in problem solving, but they do not necessarily have gut feelings for or believe in them. It is just following certain procedures, so to speak, and in this sense it is called formal. This approach applies a certain schema (here Newton's Second Law, or $F=ma$) to the situation, and the schema carries within itself a procedure for problem solving (Sherin, 1997). For Newton's Second Law, the normal procedure as presented in many textbooks is:

- Identify the forces, including their direction and strength, acting on an object.
- Calculate the vector sum of these forces as the resultant force.
- Calculate acceleration using $F=ma$.
- With acceleration, calculate object's velocity and its change.

This approach can be either quantitative or qualitative, and the latter happens when the quantities of forces are not given and subjects have to use qualitative language to describe them (such as, this force is larger than that one). If a quantitative approach is adopted, the form can be in numbers and variables. The difference is that numbers are only applicable to one context, while variables are applicable across context.

Adopting this approach, the falling situation can be conceptualized as: Weight minus Resistance→Resultant force→acceleration→speed change (→ means *causes*). Furthermore, two variations can be identified, depending on whether resistance is seen as constant or changing during the falling process. If resistance is regarded as changing, the situation becomes very complex. Thus, as object's speed increases, its resistance also increases, causing the acceleration to decrease. Although acceleration decreases, it is still downward, causing the downward speed to increase, but at slower and slower rate. If the object falls long enough, it reaches a point where its acceleration becomes zero, resistance becomes maximum (that is, weight), and velocity becomes constant which is called terminal velocity. This is the typical process of reaching terminal velocity as taught in most textbooks.

But if acceleration is seen as changing dynamically, a fully scientific approach would have to resort to such subtle features as objects' different decrease rate of acceleration to explain speed difference between objects, which is unnoticed by subjects due to perceptual insensitivities. Indeed, most subjects have not noticed the existence of acceleration in falling process, not to say decrease rate of acceleration. This implies in this case a fully formal, scientific approach is almost impossible for subjects to adopt without guidance. On the other hand, most subjects regard resistance as constant, as shown by the following excerpt:

T1	Let's use numbers. Let's say weights are 1000 and 10 (for elephant and feather respectively), so masses are 100 (for elephant) and 1 (for feather). Let's say extra force (resistance) is 3, now F1 (resultant force for elephant) would change to 997 (1000-3), so *a* (acceleration) would be 9.97 (997/100=9.97). Whereas here for the same extra force, F2 (resultant force for feather) would become 7 (10-3), so *a* (acceleration for feather) is now seven (7/1=7).
K1	That is what you said just now already.
T2	So I guess I am correct.
K2	You are correct over and over. Comparing to vacuum (elephant and feather falling in vacuum), the downward force (weight) is still the same, but now you are adding another variable, which is your three (value of resistance), then you change it (acceleration), you see. Now because of the change, right, your *a* (acceleration)

	changes proportionally (to mass). Because this (mass of elephant) is larger in the first place, a change of three will cause a smaller...smaller or larger? ...smaller change in this one (acceleration of elephant).
T3	Correct. I feel quite confused at first.

3.2.3 The intuitive approach & corresponding conceptualizations

Finally, there is the intuitive approach**.** Students adopting this approach have intuitive and gut-level feelings and understandings of concepts and principles, which are often context-dependent and flexible. Applying this approach to problem solving can often create generative and creative solutions by utilizing local resources. In this research, the intuitive approach is based on the intuitive force schema which is supposedly shared by most human beings.

In the formal approach, force is just a formal concept, but people's intuitive and everyday understanding of force is in the form of perceptual-motor schema full of muscular sensations. Human beings as biological bodies are constantly interacting with the world in the form of various kinds of forces, although they often overlook it as it has become too familiar to them. Thus, the intuitive-force-schema based approach conceptualizes the situation as various forces and their interactions, and the effect of force is regarded as directly influencing speed without the mediation of acceleration. There are quite big differences between this approach and the formal approach:

- Forces are perceptual-motor schemata with muscular and bodily sensations, not formal concepts.
- The interactions between them are also experiential schemata, such as *Fight* and *Overcome*, not mathematical symbols such as minus or addition.
- The effect of force is not based on Newton's Second law but based Ohm's p-prim (Disessa, 1993): more motive force, faster speed; more resistance, slower speed.

The empirical data show abundant evidences of subjects applying this approach in their conceptualization of the situation:

- The falling object is seen as "piercing through", "colliding with" or "pushing aside" the air.
- The action-reaction schema is applied to the interaction between object and air: air gets in the way of the object, the object pushes the air aside, and the air gives back a reaction force to push the object upward which is the force of resistance. For example, subject D explains why there is resistance: "Action force is you exerting a (larger) force on the air, the reaction force is the air exerting a similarly greater force on you".
- The action-reaction schema here is similar in form to Newton's third law, but there are two differences. Firstly, in Newton's third law, action and reaction forces are equal in strength, while for intuitive action-reaction schema, the rule is just that "larger action force results in larger reaction force" without specifying the exact quantitative relationship. Secondly, in many cases

subjects have wrongly identified the action force as object's weight. In fact, if they pursue this line of reasoning a little deeper, they will find themselves in a ridiculous position that no object can fall down, since resistance as reaction force is in opposite direction and of same strength with the weight, and the net force on the object is zero.

- The *Fight* or *Overcome* schema (Disessa, 1993) is applied to the situation so that it is seen as a fight between weight and resistance, or upward push and downward pull. A special case of fight schema is the Direct Balance schema when two opposing forces are of the same strength. More generally, these schemata belong to the *effect combination schemata*, as summarized in Figure 3.1.
- The schema "More motive force, faster speed; More resistance, slower speed" is applied to get the effects of weight and resistance on falling speed. This schema is documented in science education literature as a prevalent alternative conception, and it can be regarded as a kind of *Ohm's p-prim* (Disessa, 1993). More generally, this can be called *effect determination schema*.

3.2.4 ***The Context*** **Category**

Here context includes not just the physical context, but also the questions raised to the subjects, and together they constitute a problem context. There are three dimensions involved:

- Physical situations, which is the physical attributes of the context.
- Questions raised to the subjects. For the same physical situation many different questions can be raised, leading to different explanations.
- Sequence of physical situations. Since all the physical situations are resistance-related and similar questions are asked, solution for one situation serves as exemplar and analogy for future situations, and different arrangements of situations will influence the solutions produced.

3.2.5 *The Situational Transformation Strategies* Category

The most interesting data occur when subjects not only use the current situation to solve the problem but actually transform structure of the situation so that in the new structure the answer becomes obvious. It looks like those “aha” moments when insight occurs: suddenly the situation is viewed from a new light and everything falls into its proper place.

This strategy often occurs when there are two opposing tendencies (see figure 3.1) and subjects are initially unable to solve the conflict between them. Thus, subjects transform the structure of the situation to solve, or rather dissolves, the conflict by eliminating one of the tendencies, that is, to make weight or resistance of two objects the same so that only one factor is different. Several sub strategies are identified under this category.

3.2.5.1 Reducing Differences

This strategy simplifies the situation by reducing the differences between two objects (here to make their weights or resistance the same). For example, in the case of elephant and feather, G says

"*Maybe the density matters...Even if you slice a piece of elephant to same area as the feather, the elephant will still fall faster…it still has more mass*".

Here G recognizes the property of density as important. Since elephant and feather differ in many aspects, in order to emphasize the role of density G reduces the difference between them to density only by slicing elephant to feather. In the transformed situation, two objects have same resistance but the sliced elephant has more weight, so it falls faster.

3.2.5.2 Enlarging Differences

Instead of reducing the differences between two objects, this strategy uses *extreme cases* (Zietsman & Clement, 1997) to dramatize the differences so that the outcome becomes obvious. This enlargement is only quantitative and not qualitative in the sense that it enlarges existing difference between objects and does not introduce new kinds of difference between them. For example, in K and T's discussion of the case of iron and wooden ball, T says "*Are you sure iron ball falls faster?*" In order to persuade him, K says: "*Let's say you have a golden feather and a normal feather, they will fall at same speed?",* and later on adds *"Let's say we have a golden parachute and a parachute made of plastic. One is 10 kg and another is 1kg, I think it should make a difference."* Here the density difference between iron and wood ball is enlarged to the difference between gold and feather or between gold and plastic, making the conclusion more evident.

3.2.5.3 Transforming the situation but keeping the structure

This strategy transforms the situation but keeps the relevant structure of the situation intact, so it is better than the above two since they have changed the structure of the situation to a different one. Since any transformation will change the situation in some ways, here it is emphasized that the relevant structure is kept intact, that is, structure relevant for current purposes. As an example, the following excerpt occurs when A and J are explaining why two Styrofoam (one's surface area twice of the other) can fall at same speed:

J1	Fun, right? En, if there is air resistance, then the bigger one will fall slower, right?

A1	Maybe it can be spared (the larger air resistance can be spared by larger surface area). The total air resistance is different. But the air resistance to volume ratio is the same. Yeah.
A2	(Continues) Maybe it is like the bigger one you can cut it into two....
A3	(Later on in Session Two) This one (larger Styrofoam) has double the surface area than this one (smaller one), but this one (larger one) also has double the mass than this one (smaller one), so you split it up, it is the same. It is like two joined up.

Here several different effect-combination strategies are demonstrated (see Table 3-2). In J1 J focuses on resistance only and ignores difference in weight, so he is using Strategy 2.1.1. In A1 A changes to a different approach and uses the ratio of air resistance to volume to explain. In A2 he suggests a novel idea to cut the larger Styrofoam into two. The figure below shows immediately the powerfulness of this transformation: after cutting there are three identical objects falling, so obviously they fall at same time.

Figure 3-3 Demonstrations of how objects fall before and after the cut

This is a rare case in which subjects have successfully transformed the situation without changing its relevant structure: the large Styrofoam has the same weight, surface area and resistance with the two small Styrofoam joined together. Since here subjects are concerned with two objects' weight and resistance (and also surface area since resistance is proportional to surface area), the relevant structure consists of two objects' weight and resistance. The two small Styrofoam combined have more side areas than the large one, but side area is not part of the relevant structure of the situation, so in terms of the relevant structure of the situation, the transformation keeps it intact. This is achieved because:

- The subject is guided by his goal to find a way to reduce the difference between two objects.
- The difference is reduced by noticing the perceptual feature of the situation. Perceptually, these two objects differ only in surface area, and this makes the cut possible since the cut retains the relevant structure of the situation. The cut is not possible in the case of the elephant and feather, since elephant and feather also differ in height and density.

3.3 Conclusion

In this chapter, opening coding is adopted to allow the inductive emergence of various categories, including (categories are in bold letters):

- **Effect Combination Strategies** and corresponding **Causal Rules.**
- **High-order Approaches** and corresponding **Problem Conceptualizations.**
- **Contexts**.
- **Situational Transformation Strategies.**

With these categories at hand, the following chapter proceeds to refine, develop and modify these categories.

4 Category Development and Saturation

This chapter continues the task of category formulation by refining and saturating current categories and developing new categories. The first step is to design new instruments based on current theoretical concerns (that is, to develop and saturate categories), and the second step is to try out the instruments on new subjects and develop and refine categories based on the result. Since here we are confirming categories with just a few subjects, and this is quite different from quantitative experimental study in which large number of subjects are used, the difference between qualitative inquiry and quantitative experimental study will be explored before development of categories.

4.1 Generalizing from a few samples: the justification

In a typical experimental study, large numbers of subjects are used, the result is often quantitative numbers and these numbers are subject to statistical analysis. The assumption is that only statistical analysis over large number of subjects can guarantee the generality of the conclusion gained, and this generality may be called *statistical generality*, as the researcher is generalizing from the current samples to a statistical population. Thus, if there are one hundred samples, the samples' conditions and qualities should essentially be the same in terms of the purpose of the study, and that is the reason why subjects are often chosen on a random basis to deliberately avoid influence of subject's particular qualities on the result. Or if there is difference, it is homogenized by the large number of random subjects, and that is the reason why large numbers of samples are needed.

For qualitative inquiry, the situation is quite different. Essentially, researchers are not generalizing to a larger universe, but generalizing and developing a theoretical framework, and this may be called *analytic generality*. In choosing subjects often deliberate attention is paid to their particular qualities so that we can see how the theoretical framework plays out in different conditions and subjects. In this way, the theoretical framework can be developed, refined and finally saturated. Thus, in comparing results of different subjects, the researchers are not homogenizing them by statistical analysis but comparing the results against a theoretical framework. Thus, in this case large number of subjects is no longer needed and a few will suffice.

1 Theoretical concerns & new instruments

For the new instruments, see Appendix IV. The new instruments are developed by current theoretical concerns, as elaborated below.

Since a lot of ingenious solutions are found in subjects' explanations of falling phenomena, as summarized by **Effect Combination Strategies** and **Situational Transformation Strategies**, the number of resistance-related situations presented to subjects has increased significantly to both develop these strategies and discover new strategies. Moreover, situations are systematically organized by a certain framework, which is more nuanced than the original framework. The original framework is organized in terms of weight and resistance. The problem with this framework is that

- Weight and resistance are not independent from each other but share a common factor which is surface area: change in surface area will change resistance and weight at the same time, so that change of resistance resulting in change of weight, but change of weight will not necessarily result in change of resistance.
- The degree of coarseness of a variable is defined as the number of different ways it can be changed. In the context of this research, weight is a quite coarse variable since there are many different ways to change it. For example, to change its height, surface area and density. On the other hand, density is a much less coarse variable than weight, since normally there is only one way to change the density.

To make their causal structures more nuanced and raise their awareness of such factors as density and height, the framework of height, density and surface area is adopted. Mathematically, since in each factor there are three possibilities, in total there are twenty seven possibilities, with many duplicates and unfruitful possibilities. Thus, compared with the previous instruments, many new and surprising phenomena are added:

- Styrofoam and a small metal coin. To explain with the density/height framework, the reason why coin falls faster is that it has much larger density but smaller height. Using the weight/resistance framework, Styrofoam has more weight than coin but much more resistance. This case is revealing of the role of density.

- Two iron balls, one larger in size and diameter. The purpose is to increase complexity of the situation. Using the weight/resistance framework, it is hard for subjects to judge which falls faster since the larger ball has larger weight and resistance. Using the new framework, it is quite easy to judge: since the larger ball has larger height but same density with the smaller one, it will fall faster.
- Two Styrofoam, one's surface area twice of the other and one's thickness also twice of the other. The purpose is also to increase complexity of the situation.

4.1.1 Consolidating Categories

Some categories, due to their rare occurrence, need to be consolidated and developed. They can be consolidated in two senses. In one sense, if they appear many times in the new data, this means that the category has generality and it is a random property. In another sense, analyzing and comparing these categories to each other may produce new dimensions and properties and develop new relationship between these categories.

For the Category **High Order Approaches**, it has two sub categories, the **Intuitive-Force-Schema-based Approach**, and the **Formal & Conceptual Approach**, and only the intuitive approach is sufficiently developed, so the task is to consolidate and develop the formal and conceptual approach. Since this approach is seldom used by former subjects, it is judged that maybe subjects from other sources are needed for the full development of this approach, and we should be much certain that the new subjects would be very familiar with it. Since I come from mainland China and familiar with the educational system there, which is quite formal and conceptual, I think using subjects from China may enhance the possibility of developing the formal and conceptual approach. In total five groups of new subjects are tested, and all of them are from the SM2 batch and have just arrived at Singapore for a few months. In these few months they are mainly improving their English and not learning physics, so they have preserved their approaches to physics problem solving since coming here. The researcher's intention in this regard is fully fulfilled, but this has some unexpected consequences, however. The new subjects are so preoccupied with the formal approach that their solutions, although correct, are more mechanical and less ingenious than the Singapore subjects. See more on Section 4.2.2.

4.2 Data Analysis

The data analysis uses the emergent categories to code data, and this process can operate on either the original data or the new data, and the result can be either development of current categories or discovery of new categories.

4.2.1 Development and saturation of categories from new data

In this section, several categories and how they have been saturated and consolidated are described, especially for those categories that occur rarely.

4.2.1.1 The Effect Combination Strategies *Category*

For the Category **Effect Combination Strategies**, it has been amply consolidated and some new dimensions are discovered regarding how to determine strength of the tendency. Here some excerpts are taken from data of the new studies to show how subjects use these strategies to explain phenomena:

	Discussing which one falls faster: Styrofoam and coin
AB1	Coin faster.
GB1	The ratio of the surface to …
AB2	To the mass.
GB2	Yes. The difference between mass is smaller than the difference between surface
AB3	I mean, if this (Styrofoam's surface area) is one hundred times of this (coin's surface area), and this (Styrofoam's mass) is also one hundred times of this (coin's mass), then they will fall at same rate. But this is not the case.
GB3	Yes.
AB4	You see, this (mass of Styrofoam) is not one hundred time of this one.
GB4	Yes

AB5	We can then collect one hundred coins and compare.

Here subjects are using the rule "Object with smaller ratio of surface to mass falls faster" to explain (GB1, AB2), but they are not directly calculating the value of ratio of surface to mass for each object but indirectly comparing the strength of different tendencies: compared with the Styrofoam, smaller surface causes coin to fall faster, and smaller mass causes the coin to fall slower (GB2, AB3). Furthermore, it is discovered that subjects are determining the strength of the different tendencies in a quantitative way, which is to use the ratio between two object's mass and surface area to determine. Thus, they imagine that the larger object has a surface area one hundred times of the coin, so the tendency caused by surface area has a strength of one hundred, while the tendency caused by mass has a strength much less than one hundred, and the tendency with larger strength wins (GB2, AB3). Furthermore, this quantitative approach is of a relative mode, which means that they are using the ratio between two quantities to determine the strength.

Data in the original study (as presented in Chapter Three) shows that subjects determine strength of different tendencies in a qualitative way, using such words as "much more", "a little more", etc. In the new study, this qualitative approach is also confirmed. For example, a subject explains why coin falls faster than the Styrofoam (See Appendix III):

We can deduce why the acceleration is much faster (for the coin) is because resistance of the coin is much smaller than that of the Styrofoam although the Styrofoam is heavier than the coin. And the density of the coin is much bigger than the Styrofoam. Density is very important.

Thus, for the Category **Effect Combination Strategies**, from the data a new dimension emerges: the dimension of Strength determination of tendency with two tendencies: qualitative or quantitative (See Figure 5-6 for details). In the qualitative mode, subjects use such phrases as "much more" to denote the strength of a specific tendency, and in the quantitative mode, numbers are used to denote the strength, such as "A is one hundred times heavier than B".

4.2.1.2 *The S*ituational Transformation Strategies *Category*

For the Category **Situational Transformation Strategies**, an important new sub category has emerged: **Intermediate Case**. At first an example is used to illustrate the point. Among the phenomena presented in the new experimental study (see Appendix IV), there are three situations presented to subjects and subjects are asked to explain in each case which falls faster and why:

- Iron ball and wooden ball of the same shape and size.
- Two iron balls, one larger in diameter.
- Iron ball and wooden ball, the iron ball larger in diameter.

After having answered the first two questions, it is immediately obvious to some subjects that the third answer can be logically deduced from the former two answers, as the second situation can serve as an intermediate case between the first and third situation. Thus, iron ball with a larger diameter falls faster than iron ball with a smaller diameter (according to the second situation), which falls faster than wooden ball of the smaller diameter (according to the first situation). See excerpts below (by BG):

We can find an iron ball of the same size of the wooden ball. From the first part we know the iron ball falls faster than the wooden ball, and from the second part we know that the larger iron ball falls faster than the wooden ball, so this will pass down, so the answer is larger iron ball falls faster.

Essentially, this is also a strategy aiming at reducing the differences between properties of two objects, but it is done in a way that does not change the essential structure of the original situation. Two objects or situations (Let's say A and B) differ in many aspects, and one or a few intermediate cases, which incrementally become more and more different from A and similar to B, are introduced to make the transition from A to B not smoother and not so disrupt.

Thus, based on the above result, the original situational transformation strategies can be developed, as shown in Figure 4-1. At first, strategies that enlarge the differences between two objects and strategies that reduce the differences are differentiated, while the difference enlargement strategy rarely occurs since it is quite unusual. For difference reduction strategies, we further differentiate between those strategies that keep the essential structure of the original situation and those that change that structure, and obviously the former is preferable.

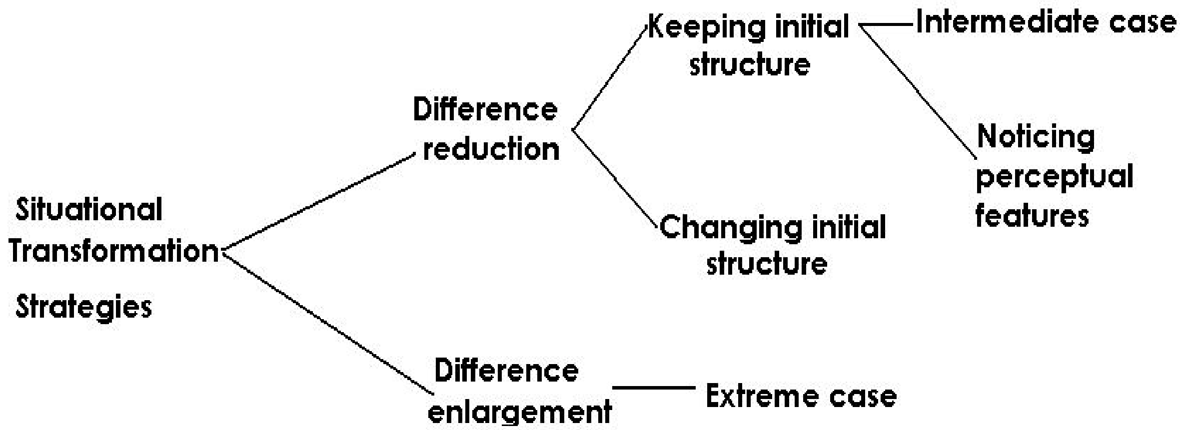

Figure 4-1: Structure of the Category *Situational Transformation Strategies*

4.2.2 Discovering & reformulating categories from the New Data

What stands out from data of the new study is the persuasiveness of the formal and conceptual approach adopted by subjects in causal explanation. Although this category is mentioned in Chapter Three, it is not fully developed since subjects seldom use them. In Chapter Three it is also briefly mentioned that a formal approach can be number based or variable based:

- A formal, number-based approach is necessarily context dependent, since numbers are specific and can not represent all the situations. This approach can be used when the question is qualitative and a more precise approach is needed. Thus, in the case of elephant and feather, the subjects can ascribe numbers to weight and resistance of these two objects and calculate their acceleration.

- For the variable based approach, since a variable can represent the generic aspects of multiple situations, it is the preferred approach of doing a formal generic analysis of a problem. Thus the name variable-based approach and generic approach will be used interchangeably.

4.2.2.1 The Generic approach

For the two approaches (number-based and variable-based), it is very obvious that the number-based approach is adopted by subjects in the initial study who are all from Singapore, and the variable-based approach is adopted by subjects in the new study who are all from China, and there are several clear patterns.

For the three approaches (the number-based approach, the variable-based approach, and the intuitive force-schema based approach), all the five groups of Chinese subjects automatically adopt the variable-based approach without explicitly being asked to do so (they also adopt the intuitive force-schema based approach. See Appendix III), and none of them adopt a number-based approach, the reason perhaps being that for them the variable-based approach is more advanced so that there is no need for the number-based approach. On the other hand, none of the four groups of subjects in the previous study adopted a variable based approach, and two groups adopted the number-based approach (K & T, Group 1; G & N, Group 4. See

Appendix II), while in most cases they adopted the more intuitive and common sense approach, such as slicing the elephant to the size of the feather (see Appendix II).

The contrast between the behaviors of these two groups of subjects thus can be characterized on two dimensions. At first, there is the difference between the formal conceptual approach and the intuitive-force schema-based approach. For the formal conceptual approach, the causal chain is: net forces divided by mass → acceleration→ speed, while the causal chain for the intuitive-force-schema based approach is "Larger motive force, larger speed; larger resistance, smaller speed". The difference between them is that in the former case force does not directly determine speed but determines acceleration, and furthermore, acceleration is determined by force divided by mass, not force itself. These two points are clearly shown in subjects' words. For example, when asked to explain why elephant falls faster than feather although it has larger resistance, one student (FG) explains: "The acceleration is resistance divided by mass, and the elephant's mass is so big, so that eventually acceleration (caused by resistance) is not so big (for the elephant)", and another student (FA) explains in a similar fashion "It (air resistance) is a force that wants to change the movement of the object, according to Newton's first law…We measure whether it is easy to change the movement of the object by the mass of the object. Since the mass of the elephant is larger than the feather, it would be harder to change the movement of the feather." Note here they are using the concept of acceleration but not speed (FA uses "change the movement" which is the same as acceleration) to explain, and they take the role of mass into consideration.

A second dimension is the role of the concrete situation or context played in subjects' causal explanations. There is a generic aspect and a concrete aspect of the context. Structurally, the generic aspect guides and structures the concrete aspect, and in temporal order information of the generic context is obtained before information of the concrete context. Thus, student behavior can be divided into two phases: obtaining generic information and obtaining concrete information. The data in the new study makes this clear since some subjects engage in long time generic conceptual analysis before applying conclusion of the conceptual analysis to a concrete situation.

The difference between a generic, variable-based analysis of the situation and a concrete analysis of the situation is that it is systematic and context independent, thus applicable to all situations. In short, nothing is assumed and local constraints and conditions are not taken into consideration. The contextual approach, on the other hand, takes local conditions, resources and constraints into consideration so that the solution is context dependent and needs to be revised or totally discarded when a new situation is presented. A generic, variable based approach would be clumsy for analyzing a certain situation, but it compensates for this inflexibility with the wide applicability of its solution.

The following example of explaining for two Styrofoam with one turned 90 degree which falls faster shows the difference between these two approaches. Faced with this situation, it is immediately obvious to the subjects that the one turned 90 degree would fall faster since it has same weight but smaller resistance, so this approach is quick and spontaneous (indeed, many subjects feel that the answer is so obvious that there is no need to speak it out). This, however, is not the case in other situations, so that the solution in this situation can't be applied in other situations. On the other hand, a conceptual approach would find a formula applicable for all situations and apply this formula to this situation, which would be much onerous, but it has the advantage of being applicable in all situations.

The generic approach, due to its generality, sort of plays a bad effect on their performance in that it inhibits them from inventing ingenious solutions utilizing context-dependent resources, since the problem can be solved in a context-independent way and the richness of different contexts are lost. This is demonstrated in several ways:

- Despite more situations (in total there are ten situations asking subjects to predict and explain which of two objects falls faster and why, and the number is six in original study) are presented to subjects, and many of them are considered as thought provoking in the sense that one object's weight and resistance are both larger than the other (of the ten situations six are of this type, while the number is two in original study), not many creative solutions are invented.
- To overcome the Chinese student's over reliance on the formal approach, the researcher explicitly asks some of them to consider other solutions to the case

of the elephant and the feather by saying something like "Ok, I accept this explanation. Can you think of other explanations, other more common sense solutions without using Newton's laws?" Surprisingly, all of those being asked fail to do so. This reflects how ingrained Newton's laws are inscribed in their heads.

The difference between a generic, variable approach and a contextual approach can be likened to the difference between algebra and arithmetic, since algebra uses variables to solve problems and arithmetic uses numbers. Many primary school students experience a sense of lost when they can solve word problems with algebra in an easy, but sort of mechanical way, while the same problem would bring much more excitement and creativity using numbers with arithmetic. For example, such problems as "One chicken has two legs, one rabbit has four legs. In total there are 50 legs, and 20 chickens and rabbits. How many chickens and rabbits are there respectively?" would be much harder to solve with arithmetic is normally considered advanced topics for primary students, but with algebra it becomes a very simple task. Furthermore, the algebra approach is general and the solution is applicable to problems of the same type, such as "One chicken has ***X*** legs, one rabbit has ***Y*** legs. In total there are ***Z*** legs, and ***W*** chickens and rabbits. How many chickens and rabbits are there respectively?"

As stated above, the data in the new experimental study makes the difference between a generic approach and a contextual approach obvious, and this important finding leads to the discovery of two new categories:

- **Causal Model**, and its two subcategories, **Generic Causal Model** and **Concrete Causal Model**.
- **Situational Model** and its two subcategories, **Generic Situational Model** and **Concrete Situational Model**.

4.2.2.2 *Emergence of the* Causal Model *Category*

The Category **Causal Model** refers to the causal model of a situation, and as stated above, it has two subcategories representing two aspects of the causal model: the **Generic Causal Model** and the **Concrete Causal Model**. The generic model guides and structures the concrete model, in the sense that the concrete causal model incorporates concrete information from the situation to flesh out the generic causal model. The following example (by FA, see Appendix III) shows the process of building generic causal model and concrete causal model.

The first step is to build a generic causal model, as shown in Figure 4-2 (mg: weight; m: mass; g: gravitational constant; a: acceleration; f: air resistance). This can be divided into two parts: the left part is the original model and the right part is the analysis. The left part is a graphical illustration of Newton's second law and can be translated into Figure 4-3.

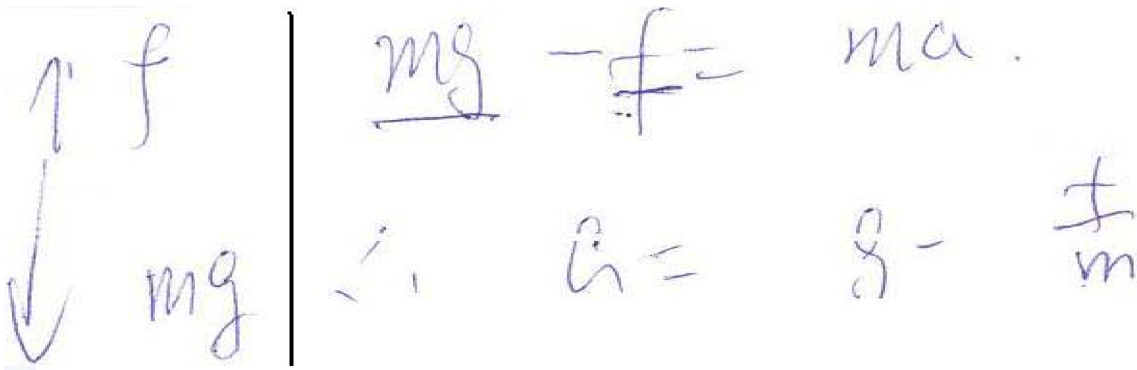

Figure 4-2: A generic causal model plus analysis of falling in the air

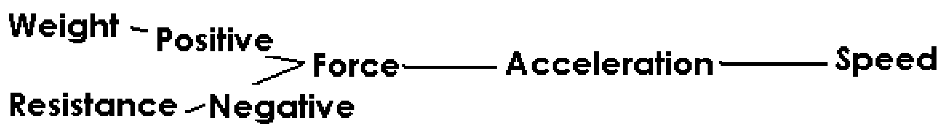

Figure 4-3: A generic, formal causal model of falling in the air

Other subjects are also able to build a generic causal model based on the intuitive force schema, so that they may regard the situation as a fight between the weight pulling down the object and the resistance pushing up the object. For example, when explaining why elephant falls faster than feather in the air, LG says: "The force that supports the object is larger than the force that supports the elephant", and later on when asked what she means by "support" elaborates: "Pushing up". The corresponding causal model is:

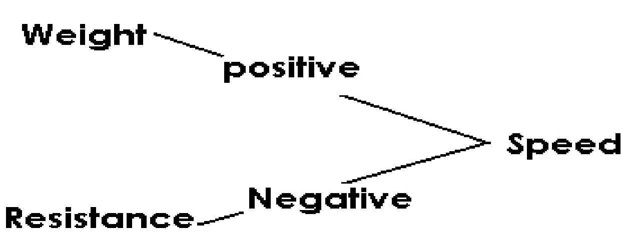

Figure 4-4: a generic, intuitive approach of falling in the air

FA then continues to apply result of the analysis to explain the situation of the elephant and the feather (Figure 4-5). Thus, a concrete causal model is built by incorporating concrete information (such as value of weight and resistance of the elephant and feather) to instantiate the generic causal model. In the generic causal model weight and resistance are abstract and general concepts applicable to all objects, while in the concrete causal model they are instantiated and become concrete with sensual qualities (for example, people would exclaim in surprise: what a heavy animal the elephant is!). After the concrete causal model is built, effect combination Strategies can be applied to the concrete causal model to produce the final causal rule. Here FA uses indirect effect combination strategies of comparing different tendencies caused by resistance and mass respectively (see Appendix III): "Resistance of the elephant is larger than resistance of the feather. However, the mass of the elephant is far bigger than the mass of the feather. So here, compared to this (resistance of the elephant), this (resistance of feather) plays a more important role (in the feather)."

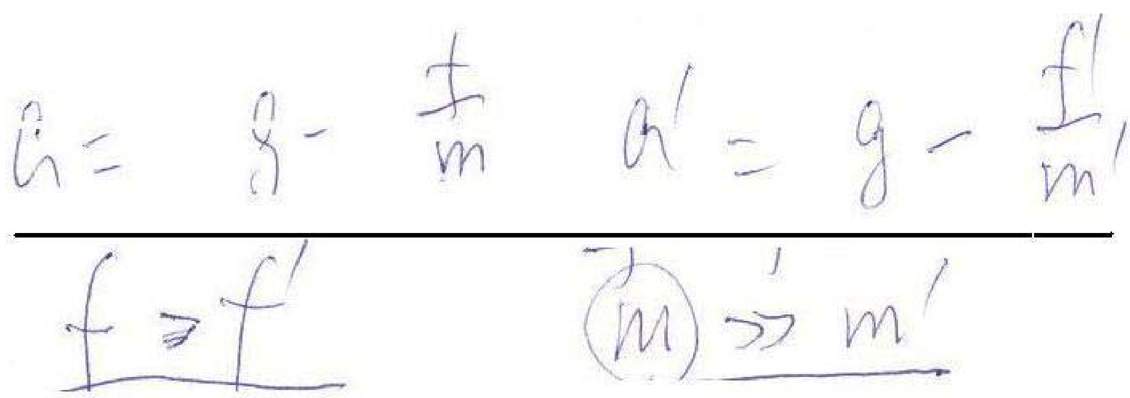

Figure 4-5: building a concrete causal model

The analysis as presented in Figure 4-2, however, is quite simple, and a more fine grained analysis made by LG in explaining why elephant falls faster than feather (see Appendix III) is presented in Figure 4-6 (G: weight; m: mass; g: gravitational constant; a: acceleration; F: air resistance;: density. The number (1 & 2) denote different objects). Note that LG thinks air resistance is proportional to volume, so she made a mistake, and here we are not concerned with the correctness of her analysis but only the way she does it. The difference between a simple analysis and a fine grained analysis is that a simple analysis leaves the current variables as they are, but a fine grained analysis tries to divide the current variables into their component variables. Thus, mass is divided into volume times density and resistance is seen as proportional to volume. The result is that new, more fine-grained variables are introduced into the situation, and the purpose is to simplify the answer.

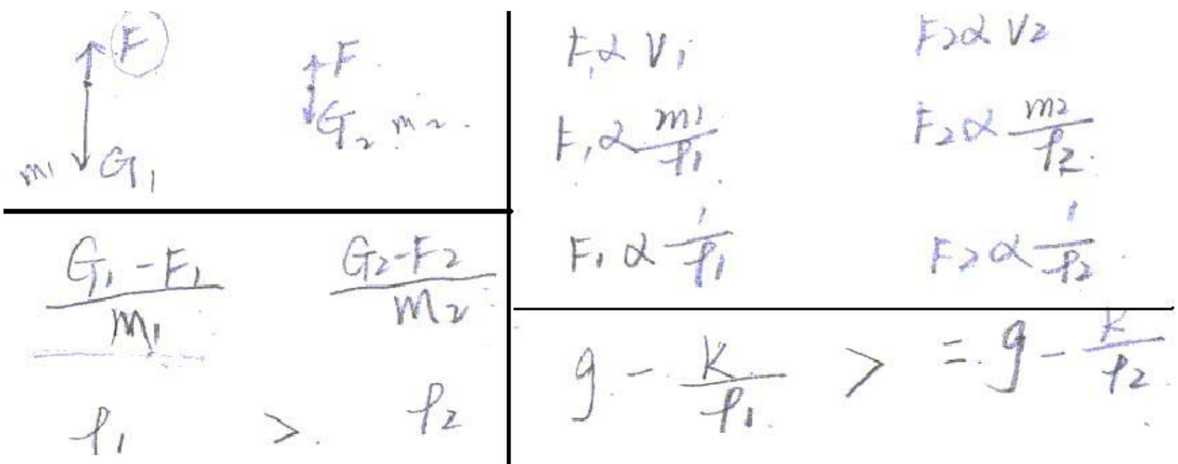

Figure 4-1

Figure 4-6 shows that although LG is analyzing a concrete situation (elephant and feather), she is not utilizing the local constraints and resources of the situation, as the analysis can be applied in any situation. Thus, a generic, variable-based approach is an analysis operated on a generic situation, and this leads to the emergence of the **Generic Situational Model** Category, which is a subcategory of **Situational Model**, as shown below.

4.2.2.3 Emergence of the Situational Model *Category*

The Category **Situational Model** is a model of the situation consisting of objects and objects' properties noticed by subjects. It has two subcategories:

- **Generic Situational Model**. It is generic in the sense that the objects and their properties constitutive of the model are generic without the sensual qualities of a concrete object or situation. Thus, when analyzing an object's falling through the air, all the components in the generic situational model are generic: the object refers to a generic object with generic qualities of weight, speed, surface area, height, etc, not a specific object (such as elephant) with its specific height, volume, etc; some subjects see a fight between the force of gravity pulling down the object and resistance pushing up the object, but these are also generic in the sense that gravity and resistance are not specified.
- **Concrete Situational Model.** The concrete situational model is built on the generic situational model and includes concrete information about the specific situation involved.

Thus, in the case of falling, a generic situational model can be of the following types:

- Two objects falling down from sky with constant speed, constant resistance and weight. This is the type adopted by most people in everyday context, since they can't notice speed change due to perceptual insensitivities.
- Two objects falling down from sky with constant weight, constant resistance, constant acceleration and increasing speed. This can be called semi-scientific, since it does not consider the influence of speed on resistance.
- Two objects falling down from sky with constant weight, increasing resistance, decreasing acceleration and increasing speed (but increasing at slower rate). This is the most accurate and scientific approach, and subjects sometimes can demonstrate this understanding when provoked by such words as "Terminal velocity" or "constant speed".

Now the relationships between these four subcategories are summarized: **Generic Situational Model, Concrete Situational Model, Generic Causal Model, and Concrete Causal Model.** At first, at a general level situational models guides and structures the causal models built, since a causal model builds relationship between various factors of the environment, and these factors come from the situational model. Secondly, at a more fine grained level, the generic situational model guides and structures the concrete situational model, and the generic causal model guides and structures the concrete causal model.

As stated above, a situational model has a generic aspect and a concrete aspect, and this is also the case for a causal model. The generic aspect incorporates general and conceptual information from the environment, and the concrete aspect incorporates concrete information from the environment. Thus, the Category **Context** is reformulated also along the line of the generic and the concrete, as demonstrated below.

4.2.2.4 Reformulating the Context *Category*

To elaborate, originally the Category **Context** is defined as consisting of the dimensions of physical situations, questions raised, and sequence of situations, etc, and it is insisted that context is problem context, not just physical context. In reanalyzing the data, especially in view of subjects' compartmentalization of scientific principles, it is found out that the original dimensions are not very useful in shedding light on the patterns of subjects' explanations. Rather, it is found out that there are two kinds of contexts: school-like context and everyday context, and subjects demonstrate their compartmentalization by using different knowledge to different contexts: book knowledge (Newton's laws) to school-like context and experiences and intuitions to everyday context, as shown in Figure 4-7.

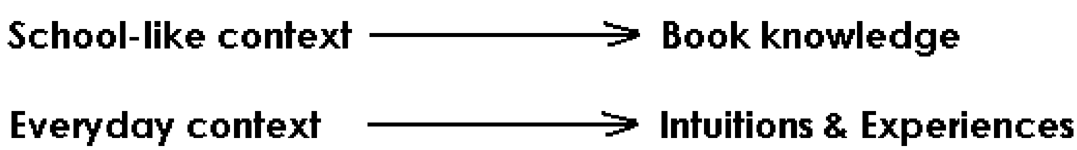

Figure 4-7: Relationship between Context and Knowledge used

Specifically, these two contexts are defined as:

- School context is the context that presents textbook-like questions. In terms of physical situations, often alien phenomena are used and students are asked to calculate the quantities of various entities, which they seldom do outside school since precision is not an important issue in everyday life. Supposedly nobody cares about the exact speed and acceleration of a falling object. Also there will be unfamiliar concepts with a scientific, book-like flavor in the question, such as *acceleration* and *entropy*. If unfamiliar concepts are used, this may trigger related book knowledge. For example, *terminal Velocity* is such a concept, as many students will apply Newton's laws (that is, book knowledge) to explain the process of reaching terminal velocity when triggered by such a concept.
- An everyday context is what people will encounter in daily life. It is qualitative, not quantitative; it is relative, not absolute (For example, such everyday concepts as high/large/long are all relative terms comparing with a certain norm); it is about familiar phenomena, not alien phenomena; and there are no unfamiliar scientific concepts.

Notice that these two kinds of contexts are defined in an objective way, so there may be some differences between subjects' approaches (which are mental and subjective) and the objective definition of context. Thus, students may use a formal and scientific approach in an everyday context as defined here. For example, as presented in this chapter, some subjects automatically use a formal and conceptual approach no matter what kind of questions are raised to them, so they regard every context as a school like context. Nonetheless, the context guides and structures the approaches taken, although it is not a strictly one to one correspondence. Thus, although these subjects adopt a formal approach in an everyday context, they also adopt intuitions and everyday experiences in their explanations, which they would not do in a school exam.

The dimension everyday/school is general in the sense that many different contexts can be classified as everyday or school-like. Since context includes concrete sensual qualities which are different from case to case, it is impossible to just use the dimension of everyday/school to fully capture what a context means. Thus, context has two aspects: general and specific:

- For general context, there are two types: school like and everyday.
- For specific context, it includes the detail information of the concrete physical situations involved.

Thus, in the case of explaining why elephant falls faster than the feather, in general it is an everyday context, and it also includes the specific context which is the concrete information about the two objects: shape, size, weight, volume, their respective falling speed, etc. These two aspects are not two ends of a continuum but can be called the global and the local aspects of the same situation. They can be likened as the skeleton (or bone) and the flesh of the situation.

4.3 Conclusion

In this chapter, various categories have been developed and consolidated, and significantly, various categories have been reformulated on the line of the generic and the concrete, or global and local, so that it can better reflect the distinctions subjects make. This is achieved through constant comparison, since comparing data in the new study and original study makes two things obvious:

- There is a generic aspect and a concrete aspect of the context. Structurally, the generic aspect guides and structures the concrete aspect, and in temporal order information of the generic context is obtained before information of the concrete context is obtained. The data in the new study makes this clear since some subjects engage in long time generic conceptual analysis of the situation before applying conclusion of the conceptual analysis to a concrete situation.
- The generality of a solution to a problem depends on the proportion of effort engaged in utilizing and analyzing information of a generic nature and a concrete nature. Thus, the longer a subject engages in generic conceptual analysis of the situation, the more general the solution becomes.

5 Framework Building

In chapter three and four, various categories have been developed, refined, saturated and sometimes discarded. There are also some explorations of the relationships between these categories, but these efforts remain sporadic, not systematic. As categories aim to separate, differentiate and make distinctions, without integration these categories tend to fracture the data and damage its holistic character. In this chapter, systematic efforts are made to build a comprehensive framework to connect these categories together and built on the work of former chapters. The connection between them can be in various modes, and theoretical coding has provided many different possibilities for researchers to choose from based on their current situations and interest.

In this chapter, the iterative process of striving to build a comprehensive framework is illustrated. The first version is called *a hierarchical model of causal explanation of everyday phenomena* (Figure 5-1). To theoretically link various categories, it is proposed that causal explanation of everyday phenomena involves the interaction of three spaces (the space of causal models, the space of situational models, and the space of problem conceptualization), and they are organized in a hierarchical manner. The goal state of explanation is to find a one-dimensional causal rule stating the relationship between a single variable and the outcome (here falling speed). For example, *Weight times Distance* in the case of balance beam. Since normally a causal model has multiple layers and factors, finding such a causal rule involves continually transforming the current causal model in a space of causal models until the final causal model becomes one-dimensional, i.e., a causal rule.

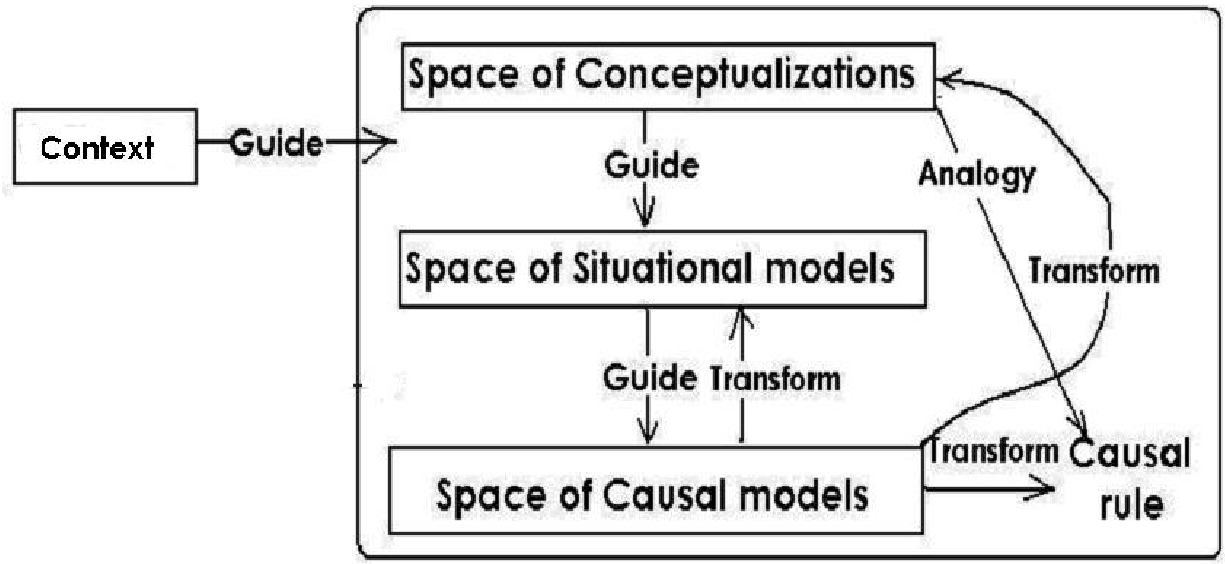

Figure 5-1: A hierarchical model of causal explanation of everyday phenomena

5.1 The problem solving framework & the idea of space

The most important decision is to adopt a problem solving framework and the corresponding idea of problem solving as searching in a problem space as proposed by Newell and Simon (1972). In the field of learning, all learning can be usefully regarded as a form of problem solving, but there can be different kinds of problem solving for different types of learning. Bereiter and Scardamalia (1989) make a distinction between learning through problem solving (i.e., learning as incidental outcome of carrying out other activities) and learning as problem solving (i.e., cognitive processes that has learning itself as a goal) which requires conscious and strategic efforts of the learner, and they use *intentional learning* to denote learning as problem solving.

Problem solving has been applied in physics textbook problem solving, and several models are proposed (e.g., Larkin et. al., 1980, Larkin, 1983). What have been most successful and predictive are models that attempts to account for sequence of steps in a solution: they trace the equations written, the sequence in which they are written, and strategies students use to arrive at a solution (Sherin, 1997). Larkin et. al. (1980) characterize problem solving as selecting equations from a database of remembered equations based on which variables appear in the problem or are wanted in the answer. A more sophisticated model is presented in Larkin (1983) in which students possess schemas, each associated with a fundamental physics principle, to guide the steps in problem solving. For simple problems, expert problem solvers show their expertise in engaging in forward reasoning: they reason from the conditions given without considering what is required as answer and are able to choose the right schema to be used in short time. For difficult problems, experts do hesitate in choosing which schemata to apply and problem solving can be regarded as a search in a space of schemata. However, even in this relatively sophisticated model of problem solving, the model is somewhat rigid and formal in the sense that the schemata, being formal and scientific themselves, contain within their structure an outline for the solution of a problem (Sherin, 1997).

Here it is emphasized that although problem solving is couched in the language of search in a problem space, this research is not committed to problem solving as symbolic activities or information processing. Indeed, this research hopes to demonstrate problem solving as situated, intricately connected with the problem context, and contingent on the various physical, social and symbolic resources available to the subjects. Subjects' flexible utilization of and on-the-fly adaptation to these resources enables them to solve problems in a flexible and generative manner, which can not be accounted for in the symbol processing interpretation of problem solving.

Adopting problem solving as framework for data analysis, it will be applied in student explanations to see what is special about explanation as a kind of problem solving, and what this research can improve on and extend current research in problem solving. Explanation is special as a kind of problem solving in the sense that the goal state is not some concrete and objective aims to be achieved (e.g., to win in the case of a game), but is epistemic and subjective in nature: to find a causal model or rule to transform an initial state of epistemic puzzles and confusions into a mental state in the subject that clears the confusion. Certainly whether the confusion has been cleared is a subjective judgment, since whether an explanation is acceptable is to some extent subjective. To take a simple example, if student A scores higher than student B, and people know A is more talented than B, the causal rule "Talent is in positive relationship to score" serves as an explanation for most people. If, however, someone objects that score does not necessarily reflect talent and there is no uniform relationship between talent and score, this rule is not a satisfactory explanation for him.

The idea of searching in a space is very important for us to provide a holistic explanation of subjects' free wheeling and opportunistic problem solving behavior. In a short time, subjects can invent many different ideas without any apparent relationship between these ideas, creating great difficulty to explain them in a dynamic manner. Suppose subjects have produced ideas A, B, C and D in a temporal sequence. To produce an explanation of student behaviors, it is not enough to just put A, B, C and D together since this is just description, not explanation. Some mechanisms have to be proposed to produce the transition from A to D, suggesting that there are some connections between A, B, C and D. The difficulty is that it is hard to find such a connection. Thus, only by regarding these ideas as states in a space of alternatives can student behavior be explained in a relatively coherent manner, that is, selecting and searching in a space.

Moreover, there is not just one space, but three spaces (the space of causal models, the space of situational models, and the space of problem conceptualization) with structural and processual (that is, temporal) relationships between them. Structurally, the causal model is constrained by the situational model, which is in turn constrained by problem conceptualization. The factors constituting a causal model are those conceptualized by subjects as relevant and significant to the situation, which are by definition part of the situational model, so the situational model provides different elements for the causal models to choose from, and in terms of number of factors the causal model is smaller than the situational model. Thus, the situational model guides and structures the causal model. In interpreting and defining the parameters of the situation (that is, conceptualization), subjects build a representation of the situation, i.e., a situational model consisting of objects, properties of objects and the interaction between objects and their properties. Thus, the situational model is constrained by problem conceptualizations. The relationship between these three factors (causal models, situational models, and problem conceptualizations) can be summarized in Figure 5-2:

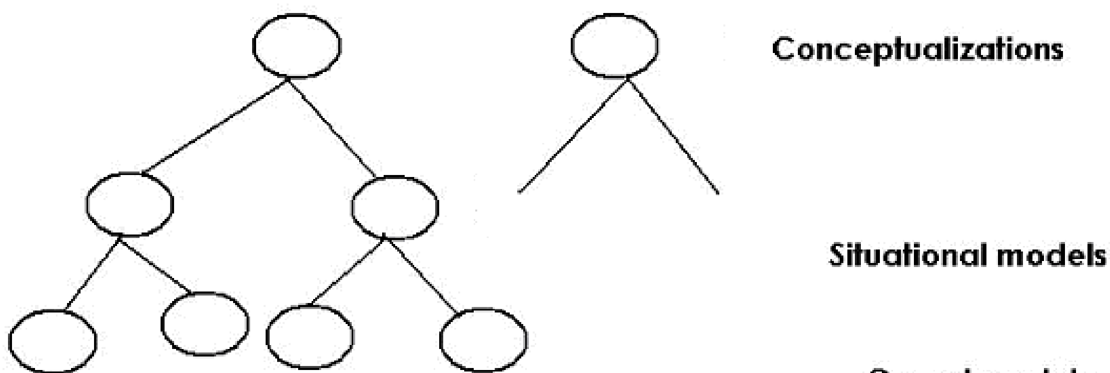

Figure 5-2: Relationships between causal models, situational models, and conceptualizations

In processual aspects, these three spaces mutually change and transform each other. Certainly change in the higher level causes change in the lower level, but what is interesting and important in this research is that change in conceptualizations and situational models can be driven by needs and circumstances in the lowest level, that is, the level of causal model, and the **Situational Transformation Strategies** Category records different strategies that can be used to transform the situational model.

There are also differences between these three spaces in terms of goal state. For space of problem conceptualizations and situational models, there are no goal states since conceptualizations and situational models are not ends in themselves but mainly serve to generate causal models, so possibly there are always better conceptualizations or situational models. For the space of causal models, a one-dimensional causal rule is the goal state which is also the goal state of the whole problem solving process.

5.2 Problems with the Original Version

The major problem is that these categories are not fine grained enough to both capture the relationship between them and reflect subjects' dynamic problem solving behavior in enough precision. As stated in chapter four, building of the situational models and causal models is not a unitary process but can be divided into two phases along the line of generic/specific. Thus for causal models at first a generic causal model is built and later on specific details of the current context are included into the concrete causal model.

There is also a problem with the space of problem conceptualizations, or with the place of the Category **Problem conceptualization** in the model. The place of the Category **Problem Conceptualization** implies that it has the same status with the other two major categories, that is, situational models and causal models. This seems not quite true. Furthermore, there should be as few categories as possible. What is the relationship between situational model and problem conceptualization? A problem conceptualization should be part of one's situational model, that is, one's representation of a situation should include problem conceptualizations. Since conceptualization of a situation is generic and does not involve concrete details, it should be the same as one's generic situational model.

Thus, the decision is made that the space of problem conceptualization is abandoned. If the space of problem conceptualization is discarded, the Category **Problem Conceptualization** should be incorporated in some other places. As stated above, problem conceptualization is the same with the generic aspects of situational model which is the generic situational model, so the Category **Generic Situational Model** is discarded and its place is taken by the Category **Problem Conceptualization**. The reason is that the model can't contain two categories with the same meaning.

Another concern is that the role of context is unspecified in the original framework, as it is not very clear how context influences various factors. Context is very important in this research, and in Chapter four it is discovered that it has both a generic and a specific aspect. The generic context should influence how the situation is conceptualized in a global manner, while specific aspect of context (that is, the specific context) will later be incorporated to make the conceptualization concrete. But context as defined in Chapter four is objective, and there is no one to one correspondence between context and problem conceptualizations. Rather, the relationship between context and problem conceptualization is mediated by the approaches subjects take to a certain situation, which is subjective and generic.

Basically, there are a generic aspect and a concrete aspect in various categories: **Context**, **Situational Model,** and **Causal model.** The generic aspect can be regarded as the concepts in terms of which people conceptualize a situation, while the concrete aspect can be regarded as the concrete instantiations of these concepts. Thus, subjects conceptualize the situation in terms of weight and resistance, and they decide the strength and value of weight and resistance from the local context.

5.3 A Revised Model

Based on the above discussion, a revised model of causal explanation of everyday phenomena is presented.

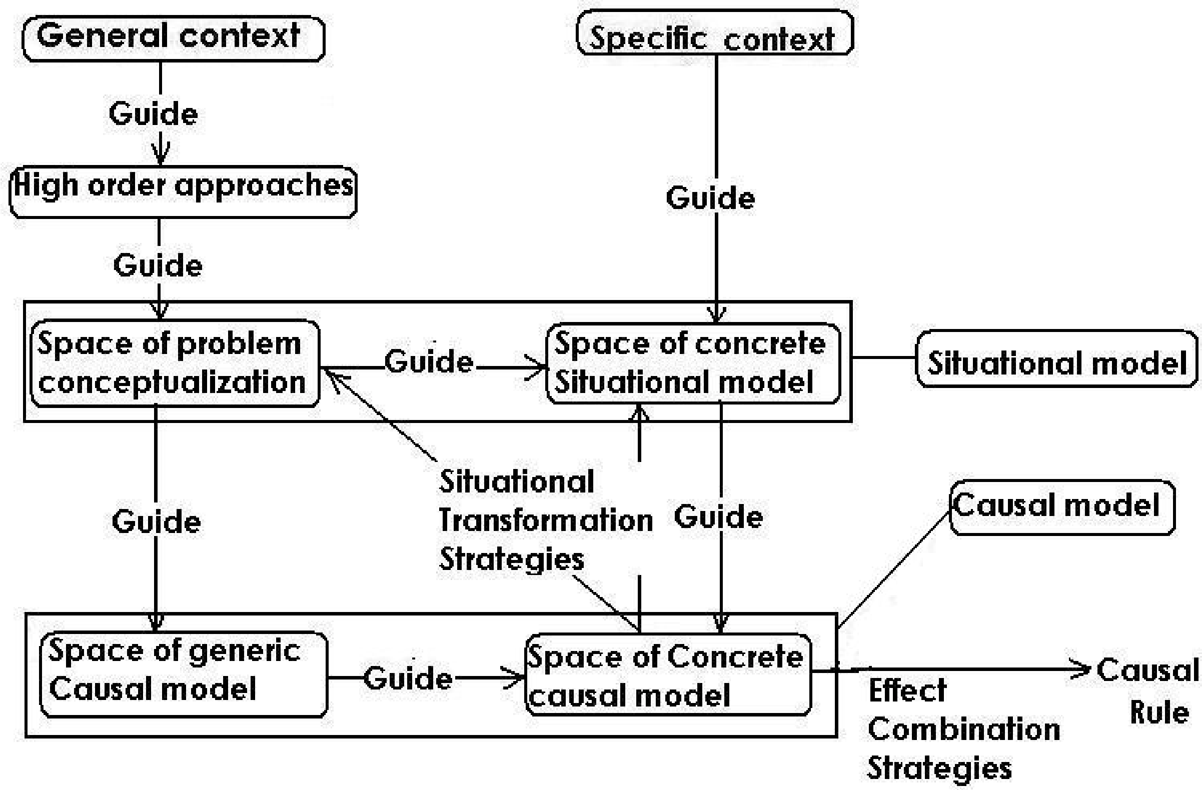

Figure 5-3: A refined model of causal explanation of everyday phenomena

5.3.1 Model illustration

To illustrate the model, at a global level, the process of causal explanation of everyday phenomena is regarded as a process of mutual transformation among two spaces: a space of situational model and a space of causal model. The model consists of three relatively static categories (the context, the situational model, and the causal model) and two dynamic categories (the effect combination strategies and the Situational Transformation Strategies).

- For the three relatively static categories, they are organized along the line of generic versus concrete (or specific), and the generic aspect guides and structures the concrete aspect. The validity of this distinction can be seen from student behavior. For example, in terms of causal models, all of them have the idea that "weight increases, speed increases; resistance increases, speed decreases", which is a generic causal model not concerned with the specific details of the current situation. These details are further incorporated into the generic causal model, transforming it into a concrete causal model so that local resources can be utilized.

- For the two dynamic categories, they are concerned with transforming causal models and situational models respectively. They are context dependent and local, so that they can utilize the local resources and invent new solutions. The Effect combination strategies are relatively saturated, since there are not many ways to combine different effects. The Situational Transformation Strategies, however, seems inexhaustible as there are hundreds of ways to transform the situation, and here the main focus is on utilizing perceptual resources of the environment. Another characteristic of the Situational Transformation Strategies is that these strategies are aimed to reduce the difference between two situations to make comparisons between them obvious. This characteristic is also shared by the Effect Combination Strategies which are also aimed at combining effects of different factors to reduce the dimension of final result to a single, one-dimensional factor. Thus, these two categories can be grouped into a higher level category: **Dimension Reduction Strategies**, which can be done either by transforming the causal model or by transforming the situational model.

- These five categories arises from and sticks close to student data, thus both students and teachers will readily recognize these categories and be able to benefit from this theoretical articulation of their implicit cognitive processes.

In the following sections, various categories and relationships between them are described in detail, starting with the Category **Context**.

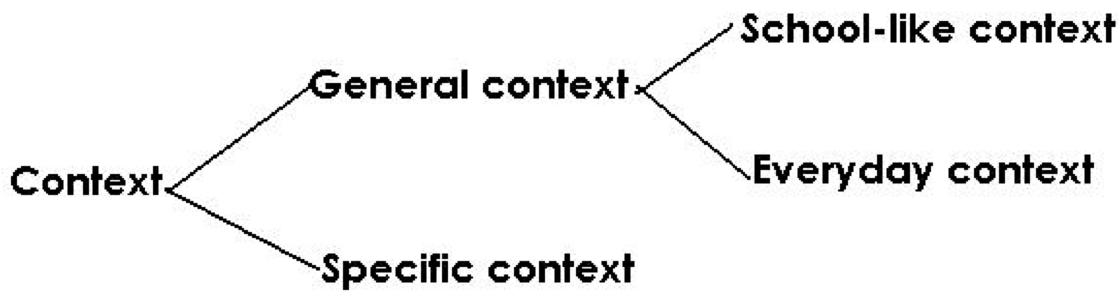

Figure 5-4: Structure of the Category *Context*

The Category **Context** is formulated along the line of generic/concrete (or specific), which are not two ends at one continuum but two aspects of the same context: the global and local aspects of the situation. For general context, it can be a school-like context or an everyday context, and they are defined in an objective way, not as perceived by subjects which is subjective. Subjects' general, high order ways of problem solving is captured by the Category **Approach**, which is subjective (see Figure below).

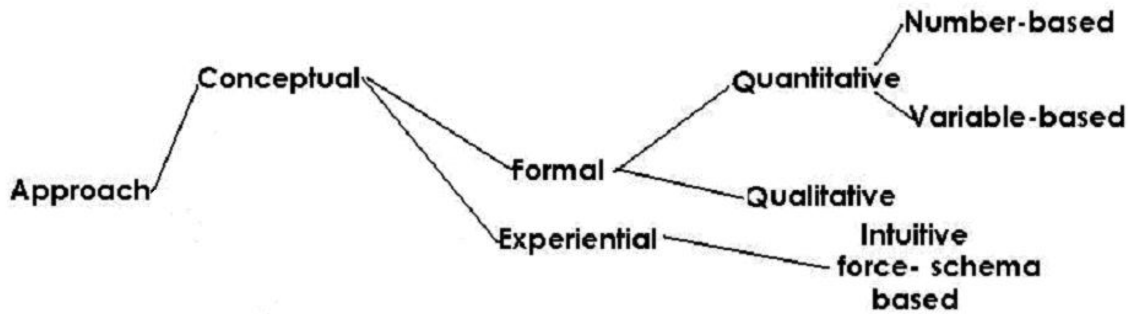

Figure 5-5: Structure of the Category *Approach*

There are two different approaches to problem solving, the formal and experiential, and they all belong to the conceptual approach. For the formal and conceptual approach, it can be qualitative or quantitative, and the latter can be further divided into a number-based approach and a variable-based approach. Normally people differentiate between an experiential approach and a conceptual approach, but here we regard the intuitive approach as also conceptual, according to the discussion in Section 1.4.2.

For the Category **Situational Model** and **Causal Model**, they are also formulated along the line of generic/concrete, so there are generic/concrete situational models and generic/concrete causal models. Respectively, they denote the general, conceptual aspects of a situation and concrete, contextual aspects of a situation with the former guiding and structuring the latter. The general and conceptual models describe the terms and concepts in terms of which people conceptualize a situation and the relationship between these concepts or terms. Thus, in the case of falling one type of problem conceptualization would conceptualize the situation as a fight between the weight and resistance, and the corresponding generic causal model specifies the relationship between weight, resistance and falling speed.

Although the generic model (both situational and causal) guides and structures the concrete model built, the concrete situation has a degree of richness and compellingness not captured by the generic model, so that the concrete model can also influence the generic model. Thus, in the case of falling of coin and Styrofoam, the situation immediately calls for an explanation based on density (that coins falls faster since it has much larger density), since the contrast of density between two objects are very great.

At the next step, there are the categories of Effect Combination Strategies and Situational Transformation Strategies, which transform the causal models and situational models respectively (See Figure 5-6 below).

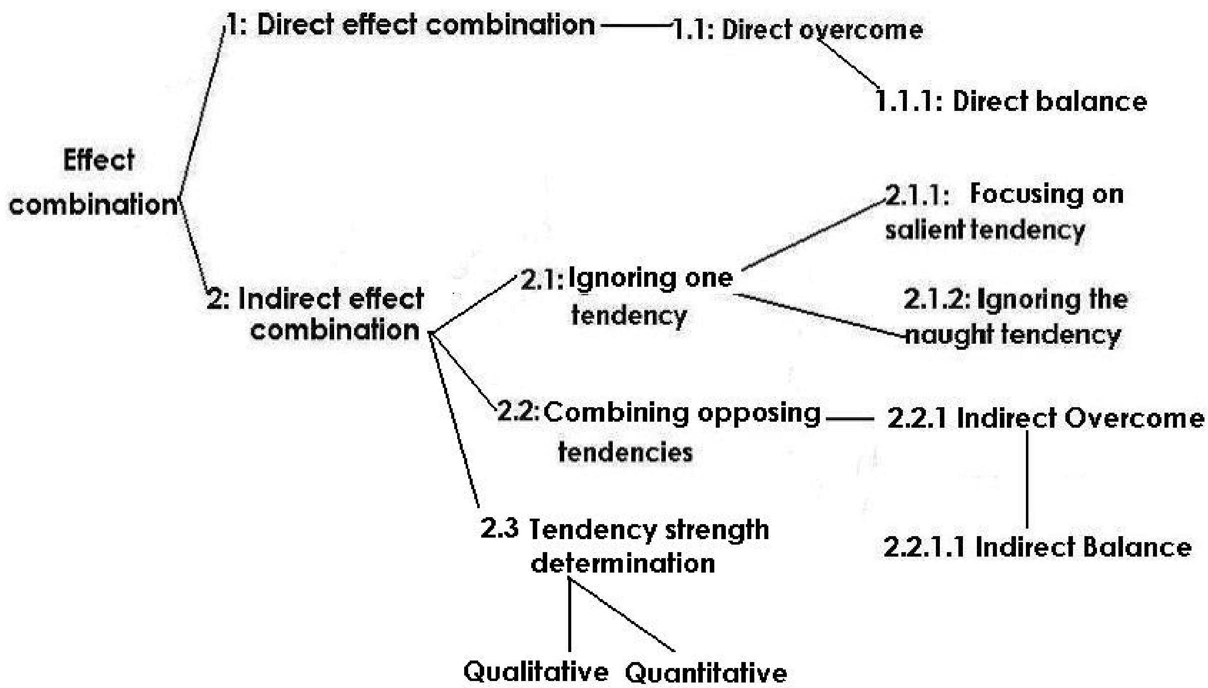

Figure 5-6: Structure of the Category *Effect Combination Strategies*

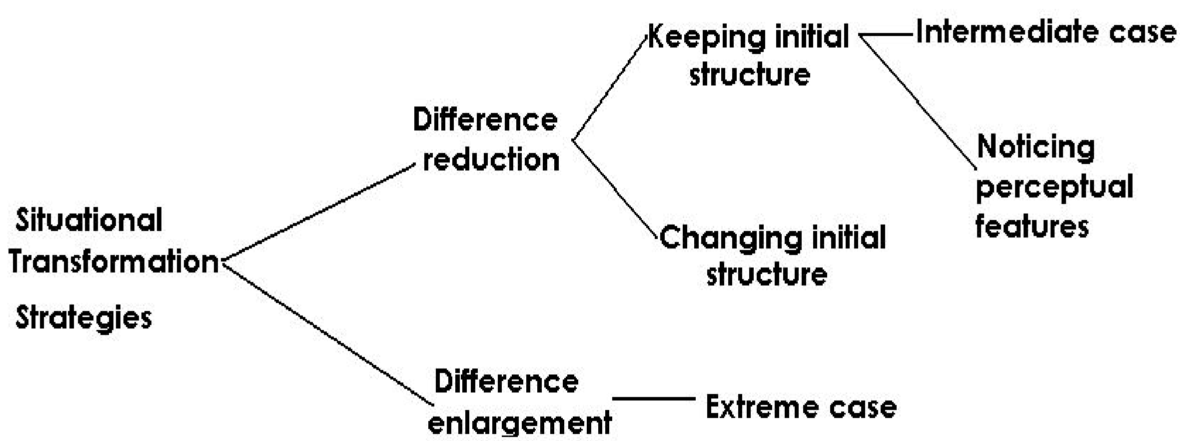

Figure 5-7: Structure of the Category *Situational Transformation Strategies*

For the Situational Transformation Strategies, it can be in different forms:

- Difference enlargement. This strategy uses extreme cases to dramatize the situation and make the situation obvious. This is used quite rarely, since it is unusual to enlarge the difference.

- Difference reduction, which can be in two forms:
    - Conserving the initial structure of the situation. Here initial structure of a situation refers to those aspects that are relevant for current purposes. This can be done in two ways: either directly transforming the situation but preserving its essential structure (such as cutting in the case of two Styrofoam with one larger in area), or indirectly finding intermediate cases between two falling objects so that the contrast between them is divided into two smaller contrast between the intermediate object and the two falling objects respectively.
    - Changing the initial structure of the situation. Slicing elephant to the size of the feather is a case in point.

As stated above, there are structural and processual relationships between different categories. The whole model is formulated along the line of the generic/concrete, and this provides a guide for relationships between all the different categories. Thus, in structural aspects, the generic situational/causal model structures and guides building of the concrete situational/causal model, and these two kinds of models (generic/concrete) are guided and constrained by the general and specific context respectively. In processual aspects, the temporal order is that building concrete models follows building general models. After these concrete models are built, different context dependent strategies are used to either transform the causal model or the situational model by utilizing local resources.

5.3.2 Generality of the comprehensive framework

Although this is a framework grounded in causal explanation of specific phenomena, that is, phenomena related to air resistance, the categories developed have a level of generality that transcend the specific phenomena at hand, so the framework can be regarded as a formal framework of causal explanation of everyday phenomena. Specifically:

- Causal explanations of any phenomena can be regarded as transforming a causal model of the phenomena into a single-dimensional causal rule, since ultimately the causal model consisting of multiple levels and multiple factors needs to be reduced to something that is one dimension. Thus, effect combination strategies, aiming to deduce the dimension of the causal model, would be relevant for causal explanation of other phenomena.
- Causal explanation of phenomena would involve representation of the situation and representation of the causal model. Both of them would have a generic aspect and a concrete aspect. The generic aspect involves the concepts or factors in terms of which the situation is conceptualized, and the concrete aspect would incorporate details from local resources to show how these concepts or factors are instantiated in a certain environment. The concrete contextual information and local resources, in turn, are utilized by the effect combination and situational transformation strategies to transform the concrete causal model and concrete situational model to produce a one-dimensional causal rule for causal explanation.

Furthermore, the two types of strategies proposed (Effect combination and Situational transformation) have wide generality beyond the phenomena under study. Since in everyday life people are always in a certain situation, and different factors push them in different directions, the effect combination strategies inform them how to combine influences of different factors to make a decision, and the situational transformation strategies tell them how to transform the situation to make it suit their own purposes better. These two kinds of strategies are also contextual and different from situation to situation.

5.4 Conclusion

In this chapter, a comprehensive Framework is built to both unify previous work and reflect the major distinctions subjects make in finding causal explanations of everyday phenomena. A framework should integrate different categories in a tight structure. The three main categories (context, situational model and causal model) are organized along the line of generic versus the concrete, so there is a high degree of coherence to this framework. Furthermore, these categories should be familiar to practitioners and students since they arise from the data. Thus, this framework satisfies the condition of fitting and logical coherence of a theoretical framework.

Since framework development is an iterative process and great conceptual effort and sophistication are needed to build a good framework, there are a few shortcomings in the comprehensive framework presented here, such as:

- Some student data and behaviors can't be easily accommodated by this framework.
- The problem of saturation. Supposedly this is a problem for all practitioners of qualitative research, since there is always the possibility of not enough saturation and new study may bring fresh perspectives. In this study it is felt that the Category **Situational Transformation Strategies** is not saturated enough, since there are many possibilities of transforming a situation.
- If time permits, new study can be done to develop the theoretical framework and bring it into full play in different conditions, and new phenomena other than air resistance can be tested to improve and develop the framework.

It is hoped these shortcomings can be overcome in later work.

6 Contributions and Implications

This chapter is the last chapter of the thesis, and here we review the various topics discussed in former chapters, and discuss the contributions and implications of this research in various aspects for education in general and science education in particular.

6.1 Contributions to model-based learning

Current research in model-based learning focuses on building explicit models of phenomena guided by scientific principles (Gobert, 2000), and the models built are context-independent applicable to phenomena of the same type. This research is contrary to these trends, thus it would complement current model-based research in several ways:

- The explanations offered are intuitive, context-dependent, not scientific and context-independent.
- It clearly differentiates between the conceptual, general aspects of model building and its concrete, contextual aspects, while current research focuses on the conceptual and general aspects.
- It is dynamic and offers a fine grained illustration of model building and transformation as the interaction and transformation of multiple spaces.

The most important contribution to this field is the development of a tightly structured framework of model building and transformation. The framework consists of various categories, these categories are densely developed, and they are tightly coupled in a systematic way.

To see the contribution, we may compare the current work to a closely related, highly influential work by the model-based learning group led by David Hestenes. In a series of articles, Hestenes and the modelling instruction program at Arizona State University have made important contributions to science education in general and physics education in particular, and furthermore, the contributions include both formal and intuitive aspects, making a comparison between their work and current work possible and interesting.

For the intuitive aspect, based on the research in common sense understanding of motion (Halloun and Hestenes, 1997), Force Concept Inventory (Hestenes *et al.*, 1992) has been proposed as an inventory of students' intuitive understanding of motion and an instrument for measuring students' conceptual understanding of the Newtonian concept of force. It can be used in various research and instructional purposes. For example, as a diagnosing tool, it can be used as pre-test so that students' misconceptions in Newtonian mechanics can be detected and instructional activities can be planned to eradicate these misconceptions, and it can also be used as a post-test to evaluate students' conceptual understanding of Newtonian mechanics.

For the formal aspect, modelling has been proposed as the name of the game of science (Hestenes, 1992) and a comprehensive framework of model-based learning has proposed in which "the basic principles of Newtonian mechanics can be interpreted as a system of rules defining a medley of modeling games. The common objective of these games is to develop validated models…..The main idea is to teach a system of explicit modeling principles and techniques, to familiarize the students with a basic set of physical models, and to give them plenty of practice in model building, model validation by experiment, and model deployment to explain, to predict and to describe physical phenomena."

The two aspects of research discussed above are highly influential and successful, but nonetheless, as in any scientific research there are many loopholes and shortcomings, and here we want to demonstrate how and in what aspects the current research complements and improves on it.

The biggest shortcoming is the discrepancy and disconnection between the formal and intuitive aspects. The formal aspect is concerned with utilizing scientific knowledge to develop and validate conceptual models of the environment, while the intuitive aspect is concerned with students' common sense knowledge of motion and no research is done to explore how this common sense knowledge are utilized in building models of phenomena. So there is a discrepancy between these two aspects. Furthermore, there is no effort to build bridges and find connections between these two aspects. Although the author adopts the language of conceptual change and demonstrates that students have improved their conceptual understanding by adopting the model-based approach, this has nothing to do with students' intuitions and everyday experiences. As the title of Hestenes (1992) suggests, it is just a game and you will win the game just by following the rules. Thus, the current research complements it by building bridges between scientific understanding and intuitive experiences and integrates them into a coherent framework.

Another problem with the above research is that it does not explicitly address the problem of causal explanations of phenomena which is central to scientific research. It is true that a large part of scientific research is concerned with building models of objects, processes and situations, but there are different kinds of models serving different kinds of purposes. Scientists and engineers both build models, but their model building activities are quite different given their different purposes. Generally speaking, engineers' goals are practical in nature and are concerned with problem solving and system design which has not so much to do with explanation, while scientists are concerned with building and improving theories and conceptual frameworks, and explanations are central to this goal. Thus, this research improves on the research by Hestenes and his colleagues by explicitly proposing explanation as the goal of model building in science learning and explores the dynamic processes of building models to causally explain everyday phenomena, as shown in the following section.

6.2 Contributions to research in causal explanations

There are many studies on students' intuitive causal explanation patterns and the differences between these patterns and scientific patterns. For example, according to some studies, intuitive causal explanations adopt a linear causal reasoning pattern (that is, A causes B, B causes C, C causes D, etc. See Viennot, 2001) while in scientific reasoning the several factors operate at the same time (A, B and C operate on D simultaneously). Grotzer and Perkins (2000) summarize current work in causal reasoning patterns and offer a comprehensive taxonomy. The taxonomy is organized in a hierarchical manner. At the top are four general types of causal reasoning patterns (**Underlying Causality, Relational Causality, Probabilistic Reasoning and Emergent Causality**), and in each general pattern there are more specific patterns organized according to levels of complexity of the causal reasoning patterns involved. Thus, in **Underlying Causality**, the simplest subcategory is called **Surface Generalization** with no underlying mechanisms, and the most complex subcategory is called **Underlying mechanisms** which uses underlying entities and properties to explain surface generalization.

The above work is introduced in detail since it summarizes many related work. Interestingly, the title of that work is called "A taxonomy of causal models", so that the difference between causal models in their work and causal models in current work can be compared:

- The causal models in their work are at high level of generality and do not probe how students seek causal explanations for concrete phenomena. To causally explain a concrete phenomenon, phenomenon-specific models must be built, and there are both general aspects and concrete aspects involved in these models, thus they are context-dependent.

- The dynamic process of building and transforming models are not explored.

To make up for these gaps, this research explores the contextual and processual aspects of students' dynamic causal explanation behavior in a concrete situation of comparing falling speed of different object:

- It is contextual and situation-specific. People's causal explanations in everyday life are contextual, flexible and generative utilizing local resources. Local resources are utilized in two senses:
  - The final causal rule is context dependent.
  - This is achieved by utilizing local resources (as different Effect Combination Strategies show), and sometimes even transforming the current situation to build a better causal model.
- It is processual and concerned with the dynamic processes of model building and mutual transformation of causal models and situational models.
- The framework is formulated along the line of the interaction of several spaces each with its own alternatives, and this greatly increases the number of possibilities of the final result.

6.3 Contributions to problem solving research

This thesis develops a framework of causal explanation of everyday phenomena. Since it is formulated in a problem solving framework, it contributes to the general field of problem solving. Here the contributions are demonstrated by showing its improvement over the prevalent problem-solving framework as proposed by Newell and Simon (1972). This comparison is revealing because the current study adopts the basic vocabulary of their framework, so it both inherits vocabulary and language from them and tries to make some improvements, which also makes the comparison easier since the same vocabulary are used.

The basic vocabulary in Newell and Simon (1972) is search in a problem space. Problem solving is seen as a continual transition between problem representations (or problem states in a problem space) until a goal state is achieved, and the transition is caused by problem-solving operators which operate on and change the problem representations. There are several differences between the problem-solving framework proposed here and Simon's model. Simon's model is formal, context-dependent and symbolic in nature, and has been realized and simulated on many computer simulations. On the other hand, model proposed in this research is conceptual and contextual. For the problem states in a space, such as overall problem conceptualization (an example would be to conceptualize falling as fight between downward pull and upward push), they are conceptual and not easily simulated on a computer. For the problem-solving operators (effect combination strategies and situational transformation strategies, for example), they are contextual and utilize local cues and resources in a flexible way (sometimes to the extent of transforming the situation), thus these operators are quite different from the formal and symbolic operators in Simon's model.

Another contribution of this research to problem solving is to expand from one space as in Simon's model to multiple spaces, and problem solving is seen as a process of the interaction between different states in these spaces. This has several advantages:

- A much larger space of possibilities is created since there are several different spaces interacting with each other. Mathematically, the number of possibilities of several spaces interacting together is the multiplication of all the possibilities of these spaces.
- The interaction between various spaces captures the subjects' flexible, context-dependent, generative and opportunistic behaviors very well. For subjects, all kinds of knowledge and experiences (whether it is intuitive or formal) have roughly the same status and can serve as alternatives and resources for problem solving.

The expansion from one space to multiple spaces is not rare. For example, Scardamalia and Bereiter (1984) propose a dual-spaces model of written composition (the rhetorical space and the domain content space), and Klahr and Dunbar (1988) proposes a dual space search in scientific reasoning (The hypotheses space and the experimental space). Here contribution of this study lies in expanding the spaces successfully in the field of students' causal explanations of everyday phenomena.

Seeking causal explanation is central both in people's everyday life and scientific research. Science strives to find causal explanations unifying diverse phenomena, so they are central in scientific research. Seeking underlying reasons and asking "why" questions are also mundane affairs in people's everyday lives. Apparently there is vast difference between causal explanations in these two settings, as in real life the information is often imprecise, messy and ambiguous, and most importantly, causal explanations need not strive to be general and all-encompassing as the purpose is oriented towards practical ends.

6.4 Implications for Constructivism and Situated Cognition

To some degree this research offers evidence in support of constructivism and situated cognition. Recall that the initial learning environment has a relatively unstructured part (phenomena explanation) which receives little attention in the design stage and has an everyday flavor, and it also has a more structured and scientific part (process models building and causal model building). The unstructured part, however, turns out to be the most productive for the students and many ingenious explanations and solutions are produced. Students also engage in long time and heated discussions, which is not required by the environment. This shows that explaining novel phenomena can ignite and motivate student interest. On the other hand, students are not so interested in the latter two parts, and they seem to just regard it as a task to be finished which is to build the models. After all, this is what is required of them. This seems good evidence in support of constructivism that students are more active and learn more in a relatively unstructured environment, if that environment arouses their interest. Furthermore, students' ingenious explanations are context dependent, generative, created on the fly utilizing the current physical, social and symbolic resources in a flexible way, while their model building activities are relatively mechanical and routine. This seems good evidence in support of situated cognition.

The educational implications, however, are not easy to draw. While students' explanations are productive, it is also chaotic, incoherent, opportunistic and full of ambiguities. It is not clear where this kind of active but chaotic learning experiences lead to and what benefits students gain from them. Students are engaging in interesting discussions, they are motivated, and some of their explanations are quite ingenious, so certainly this kind of learning experiences is good for them, but the problem remains how to integrate this kind of experiences into a school learning context. After all, students should have a firm grasp of Newton's laws, but there is no need of Newton's laws for many students in explaining phenomena. Common sense is enough. For the students who use Newton's laws in a systematic way, the task becomes applying a context-general formula to all the situations. This again leads to the problem of the relationship between concrete experiences and disciplinary knowledge, and between the school environment and students' everyday life. Since school learning is closely associated with the notion of grasping systematic disciplinary knowledge, this problem is especially acute if people want to make school learning more unstructured and active.

Furthermore, students' relative inactivity in the sessions based on scientific principles may reflect their relative incompetence in engaging in discussions at the conceptual level, so the solution is not to abandon this kind of activities but to foster their abilities to work at the conceptual level and not solely focusing on the experiential and phenomenal level. This leads us back to the issue of the relationship between concrete phenomena and abstract theories, and between scientific practice and people's everyday activities.

6.5 Future Work and conclusion

This research raises more questions than answers, thus there are a lot of future work that can be pursued. Also the lines worthy of further inquiry are many, such as inquiry learning, model-based learning, computer-based learning environment, etc. The following is a short list:

- If conditions allow, long time classroom research can be pursued to explore the effect of promoting student conceptual understanding of mechanics by engaging them in building process models and causal models.
- The design of computer-based cognitive tools can be improved.
- The problem solving framework presented in this research can be tested in other field and possibly generalized to a higher level.

- Model based learning can be researched in other fields and other models can be built so that a more comprehensive understanding of model based learning is achieved.

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Appendix A: Transcripts of Initial Study

Legend:

m: Mass	h: Height	V: Velocity	V: Volume	r: Radius
A: Acceleration	g: Gravitational constant (9.8)	D: Density	S: Surface area	

1 Transcripts for K & T

	Why air resistance is larger when you are running?
K	Action and reaction thing lah, right?
T	Actually I am not sure.
K	Because when you run, right, then you like exerting a greater force on the air. (T: Yes) So the air gives you a greater force, right? (T: Yeah) (Reading) When you are walking, air resistance...it is very small. Same thing.
T	Right.
	Discussing the question of skydiver falling from sky
K	Parachute lah.
T	Why?
K	Surface area. Because as you open parachute right, there is greater air resistance. Because air resistance is upwards, so it counters the downward force, and since it (air resistance) is greater, so it (skydiver) will slow down. (Air resistance) will be greater than...the downward force.
T	Ah? No you are all wrong.
K	Then what you say?
T	Because upward force provided by the parachute is larger than the downward force provided by the person's weight.
K	Yeah, that is what I say.

T	No, you say the other way around. Ok, never mind. So therefore there will have a deceleration because there is a resultant force upwards. So the velocity downwards will become smaller because there is deceleration. Yes, because F equals ma.
K	That is nonsense (in a joking tone)!
T	Yes! So the resultant force upward will result in an upward acceleration which is like deceleration downwards. Ah, I got it (laughing happily)!
K	I thought w equals mg.
T	F equals ma and w equals mg.
	R Points out that in pretest K thinks force and motion has to be the same direction. Here velocity is downward, how about force? Why it is not downward?
K	You have to slow down first, right? The total force is upward, but object is moving downward, that is why you are in deceleration!
T	You see, force gives acceleration, not the direction. So at first it is dropping very quickly but now with air resistance it is decelerating, but it is still dropping! Then when it comes to the point, it will be, yeah, the downward force provided by the weight and the upward resistance will be equal. So it will be constant.
K	That is terminal velocity.
	Iron ball and wooden ball
K	Why the iron ball falls faster? Because it is heavier, right, greater mass.
T	Two balls of same shape and same size, so surface area is same, so air resistance is the same. So in this case air resistance for both objects are the same. But whereas...you see the...
K	Wait...If one is heavier, right, air resistance on it will be greater, because it is exerting greater force on the air, so air resistance is greater for iron ball, right.
T	En.
K	Weight is mg, right, so the weight of the iron ball is greater. Does it mean the total downward force of iron ball is greater than the one on the wooden ball, so it falls faster.
T	No, no, It depends on.. At first I thought wooden ball fall faster. It depends on...
K	No. Iron ball falls faster.
T	Are you saying that It depends on (weight)... for iron ball is greater than the wooden ball?

K	Yes, isn't it?
T	So wouldn't iron ball and wooden ball fall at same time? Because...because the weight of iron ball is larger, but the air resistance of iron ball is also greater than the wooden ball, so it will counter-balance, and they will fall at the same speed.
K	Let's say the iron ball has weight of 100 Newton, and the wooden ball is 10 Newton, right. As it falls down, the rate of the acce gain is slower for the...100 Newton one. The wooden one would just reach terminal velocity faster. For the iron one it takes longer to reach terminal velocity.
T	Why?
K	Because it is 100 Newton, and it starts from zero, right. So if terminal velocity for the iron ball is higher, it will fall faster than the wooden ball.
T	Doesn't make sense. Are you sure iron ball falls faster?
K	It is not a vacuum, right? Just as an elephant and a feather.
T	It is different. (For elephant and feather), my answer is surface area to volume ratio is greater for the feather, therefore there is more air resistance. But here I don't know, because you are looking at mass. I don't know if mass actually affects.
T	Mass affects. Because weight equals mg, so if one object is heavier than the other, it falls faster.
T	Then the air resistance likewise increases...you know what we are dealing? We are dealing with air resistance, so we have to first derive the difference between air resistance. Because g is 9.8. G acts the same on all objects, so it is only air resistance that determines how fast object falls. Because...
K	Let's say you have a golden feather and a normal feather, they will fall at same speed?
T	That one I am not sure. Here we must first determine whether air resistance is the same for both the iron ball and the wooden ball.
K	Let's say we have a golden parachute and a parachute made of plastic. One is 10 kg and another is 1kg, I think it should make a difference.
T	I can't determine the iron ball or the wooden has more air resistance.
	Clumped paper and normal paper
K	The one that clusters falls faster, right? There is air resistance.

T	Yes
	Two Styrofoam, one turned 90 degree
K	Because when it is wider, right, it has greater air resistance, and it counters downward force which is the same, so it falls slower. This is the same theory as this one.
T	Actually I am thinking from this question the surface area to volume ratio of this thing is greater.
	Two Styrofoam, one larger surface area
T	(Prediction) Actually I think this one (with larger area) falls faster.
K	(After experiment) You see, the weight of one is heavier than the other, but the surface area is also greater, so it falls at same time.
T	I was thinking they will not fall at exactly the same speed, there will be a small variation. Let's say one's surface area is three times the others, there is surface area here but there is no surface area here and here. So the surface area to volume ratio is different.
K	Not much lah.
T	That is why the difference is small.
K	But I thought only the bottom area matters and sides don't matter.
T	Really? Actually the sides matter.
k	Because the bottom is the one that is pressing against. You see this one (side) doesn't exert any force, it is the bottom that exerts force.
T	Why don't the sides...?
K	This is not the one that is causing resistance.
T	Actually yes. then they will fall at same speed.
	Two Styrofoam, one thicker
K	(Predicts) Thicker one faster, as it has same surface area but bigger mass, so...it is the same question as the iron ball and wooden ball. This one (thicker one) is like the iron ball and this (the thinner one) is like the wooden ball. If you follow (the logic of the first question?) correctly, air resistance is the same right, but the weight is greater...
T	So the weight minus air resistance for the iron ball is greater than the weight minus air resistance for the wooden ball, so the (resultant?) downward force is greater.
R	How about in a vacuum?

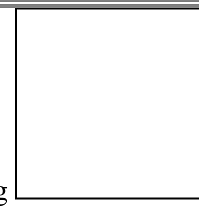
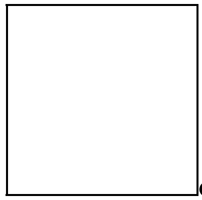
T	Actually I knew it just now...Because when it is falling down, a is just g, the gravitational force that is pulling downwards. Because you see weight equals mass times acceleration, but a (acceleration) is always the same, a makes fall at same speed.
K	Let's say elephant has a mass of 600, so its weight is 6000N, feather has a mass of 6, so the weight is only 60 Newton.
T	You see, force is just force, the weight doesn't determine how fast a is.
R	I am saying that it is wrong that larger force leads to larger acceleration.
T	Yes, so actually our theory is wrong. But I am correct. We work backwards. The resultant force of the iron ball would be greater than wooden ball since it falls faster.
K	But if you drops faster then you already confirm the acceleration lah. Acceleration is greater.
T	Our theory is that...Let's say this iron ball and this wooden ball. In a vacuum right, F1 equals Ma, F2 equals ma, it doesn't matter, because a is the same, and F1 and F2 are proportional to (M and m). With air resistance, there is an upward force that is going to resist this F, correct? But this F1 is so much bigger compared with this F2...
K	But if F is bigger then there is greater air resistance also, that is for sure. The problem is how big it is. Because if you push harder on air, air will be pushing harder on you.
T	Is air resistance an action and reaction force? I don't think so. I am thinking for the same shape same size, this two (air resistance) will be the same.
K	The same shape same size. Yeah, this one is so much bigger that it is falling faster.
T	Then why are arguing with me? Are you agreeing that these two air resistances are the same?
K	Yeah.
T	I think it has something to do with "F equals ma", a is different.
K	Yeah. That is why F is different. The question is why in a vacuum downward force doesn't matter, while here downward force affects.
T	Let's use numbers. Let's say weights are 1000 and 10, so masses are 100 and 1. Let's say extra force is 3, now F1 would change to 997, so a (for elephant) would be 9.97. Whereas here for the same extra force, F2 would become 7, so a (for feather) is now seven.
K	That is what you said just now already.
T	So I guess I am correct.
K	You are correct over and over. Comparing to vacuum, the downward force is still the same, but now you are adding another variable, which is your three, then you change it

	(acceleration?), you see. Now because of the change, right, your a changes proportionally (to M and m). Because this is larger in the first place, a change of three will cause a smaller...smaller or larger? (Looking at 9.97 and 7)...smaller changing in this one.
T	Correct. I feel quite confused at first.

2 : Transcripts for J and A

J	(Reading) Why the force is stronger when running? It is because the equal and opposite force. The reaction force.
A	En. Yeah.
J	Wait wait. ... That is it.
J	It is because what we said just now. It is Newton's third law, right? You run, you apply a ......
A	(interrupting, laughing) You apply a force on the air.
J	Is that true? You are supposed to be the (king). So what you think? ... Because you are pushing (the air), right? Let's give some input (asking for ideas from Andre).
A	The action and reaction thing la.

J	(Explaining why skydiver's speed slows down after parachute is opened.) Why it slows down? Because of air resistance. Because it has larger surface area.
A	(Reading) Why the speed slows down?

J	Because the parachute opens up, and... Actually it is like that. (Drawing  on the paper to stand for the skydiver). The surface area is small, is that true? When you open the parachute (Draw  on the paper).
A	It is very big.

J	(Reading) Why the speed can reach a constant value? Because maximum (air resistance).
A	(Reading) Reach a constant. ... Terminal velocity.
J	(at same time) Terminal velocity. Yes, yes, we learn this before.
A	Is it?
J	Yeah.
A	I guess a lot of people don't know this. I got from my friend.
J	When it is dropping, air resistance... The maximum air resistance can be (seems saying when air resistance reaches maximum, speed is constant), is that right?
A	It means... Ah, because F is ma, so if F cancels out, ma is zero, a is zero, velocity is constant.
J	(Still thinking) it is terminal velocity...
A	But do you understand terminal velocity? We are not taught
J	Constant speed? That means no more (acceleration). Max la, air resistance is at its max.
A	That means air resistance picks up, and becomes more and more (gesturing "more and more"). Then it finally balance out this one (weight).
J	Yes
A	Then a is zero. That is all (make a gesture of relief).
J	(Reading) why larger air resistance leads to faster speed. (Surprised) faster speed?
A	The elephant is faster...

J	Are you sure larger air resistance leads to faster speed?
A	No, right?
J	Smaller air resistance leads to faster speed. (Turn to researcher for help)
R	(Providing a fact) Of course for elephant the air resistance is larger.
J	No.
A	The total (air resistance) is larger. But surface to volume ratio is smaller.
J	Yeah, yeah (Seems he only understands resistance increases, but not the latter part). Amazing.
A	(Reading) Predict which object falls faster? Explain.
R	(Reading) made of wood and iron. I think they will fall the same, right?
A	Wait, wait.
J	Actually it is another example of elephant and feather.
A	Same shape but different materials. Same, it is the same.
J	En, mass (don't know what he means. Is he trying to say mass is different?).
J	(Reading) one is in a cluster. Of course the one in cluster will fall faster. Common sense.
A	Less air resistance so it falls faster.
J	(Reading) Two pieces of Styrofoam falling with different orientation. Of course picture one will fall faster.
A	Yeah.
J	Less air resistance.
J	(Explain falling of two objects, one's surface area is larger than the other) One's surface area is larger than the other. The larger surface area will fall slower. (Reading) One is twice as thick as the other. Thicker one will fall...
A	En? No, no, wait.
	(Researcher got two Styrofoam and prepared to do experiments for them: falling from a man's height)
A	But it is too short a distance to see.
	(The two pieces fall almost at the same time)
R	Almost same time.

J	No. If you watch carefully, the result would be ...
	They did the experiments for several times and the result is unstable. Sometimes one object falls to the ground first and sometimes another falls to the ground first. They also discuss the source of errors and try to do experiments in new ways to eliminate the errors.
R	(to save time, researcher gave a conclusion) They fall at same time. The difference is minimal and can be neglected.
J	Fun, right? En, if there is air resistance, then the bigger one will fall slower, right?
A	Maybe it can be spared (the larger air resistance can be spared by larger surface area). The total air resistance is different. But the air resistance to volume ratio is the same. Yeah.
A	Maybe it is like the bigger one you can cut it into two. Then...
J	What? What? I can't understand.
A	(Reading) The elephant will fall much faster than the feather when there is air resistance (why he returns to this?).
J	Because it is heavier.
A	But it also has larger air resistance.
J	The thick one and thin one, right, I think the thick one will fall faster (Here he has two conceptions: heavier one falls faster, as applied here, and the one with larger air resistance or surface area falls slower.).
A	In a vacuum is there gravitational force?
J	Yes.
A	Can we get data from this (gesturing falling objects from height of his eyebrow)?
J	Let me think for a while.
	(After a moment, J falls one paper and his point pen from his eyebrow to the table, the pen falls faster)
J	This one (the pen) falls faster.
A	(To researcher) Hi, chaochun, is this statement correct: larger air resistance leads to faster speed.
R	(Realizing the statement is not general, the researcher gave a clarification) This is a special case. I am just saying in the case of elephant and feather...
A	(Interrupting) Oh, ok. So this statement is not correct. (To J) What to do?

J	What solution do you know?
A	I don't know what is the problem.
J	(Repeating, seems frustrated) What is the problem!

3: Transcripts for D and L

D	(Nodding her head, explaining why you run faster, you feel more resistance) Yeah.
L	(Nodding her head) Yeah.
R	(So surprised at their reaching consensus without speaking out, also encouraging articulation) Can you speak out?
D	Because action and reaction thing lah.
L	So when you are running, the force is greater, similarly the force of air will be greater.
D	Action force is you exerting a force on the air, the reaction force is the air exerting a similarly greater force on you.
D	Air resistance becomes greater because there is greater surface area.
L	(Reading) speed stays constant. This is terminal velocity, right.
D	So the resultant force is zero.
L	And the velocity stays the same because...
D	Because acceleration is zero.
L	The iron one will fall faster, because the iron one is denser than wood, so it has greater mass, right?
R	Why in the vacuum they fall at same speed although iron ball's weight is still greater?
L	Because there is no air resistance.
D	There is no air resistance, right.

L	Where are we now? We have predicted and now we are explaining. Actually we have explained when there is air resistance. Because there is greater mass, so the weight is greater, remember?
D	Yes.
L	So it falls faster when...oh...
D	But this doesn't explain why they fall at same speed when there is no air resistance.
	Two papers
L	I think crumpled one will fall faster.
D	Because the one in normal shape has greater surface area so it has greater air resistance.
L	But both of them have the same mass.
D	So it (mass) does not matter.
L	So that is why air resistance makes it falls slower.
D	So the crumpled one falls faster.
	Two Styrofoam, different orientation
L	It is the same as number two, right. The one that is falling horizontally will fall slower.
D	Yeah
	four: two Styrofoam, different surface area
D	The same as number three lah. This one has greater surface area.
L	Yeah. But this one also has greater weight. Oh, I know, I know. It is like the running guy.
D	What about the running guy?
L	It slows down. The greater weight will have greater resistance, as well as the greater surface area will also have greater surface area. So the larger one will fall slower.
D	I think it will be the same. Maybe they will cancel out each other.
L	I don't know...I think the larger one will fall slower.
	Experiment: result is the same
L	Yeah, it is the same, because they cancel out each other. It has greater weight, but it also has greater resistance, so it roughly cancels out.
	Five: Thicker
D	The thicker one falls faster because it has greater weight.

L	Yeah, greater weight. Same surface area, so same upward resistance.
D	We don't think about air resistance lah. It just has greater weight.
R	If you don't think about the air resistance, why in vacuum they will fall at same speeds?
D	So it is about the same air resistance. Air resistance will depend on weight. An object with greater weight has greater resistance, right?
L	I think it has same air resistance. Not supposed to be (depending on weight), right?
D	I am not sure.
L	It is like the water resistance right. (Turning to the window of water) Oh, it is speed, not really speed.
D	Yeah, I think air resistance is the same, although it has greater weight.

4: Transcripts for G and N

N	Maybe it is under equal action and reaction and pushing back because it is equal force in opposite direction, right?
G	Yeah, but where is the force coming from?
N	What are you talking about? The equal and ... (Explains using Newton's third law)
G	Yeah. But what is it? Where is the force coming from? Why the force is larger when you are running?
R	The problem is why if you don't walk, there is no air resistance.
N	Let's say there is a brick wall here, right, a moveable brick wall lah. You punch the brick wall, you feel the pain. But if you push the wall slowly, the brick wall will move but you will not feel anything.
G	Yeah. But when you are pushing you use hand, but when you punch you use your fist.
N	Let's suppose you use the same surface area.
G	OK.

N	Let's say the brick wall is air, right, because When you are walking straight, right, I suppose, air or water will just like fish streamline body. The air would just slowly slide pass you. When you are running, wind strikes you at ninety degree. So it strikes harder, it pushes, it doesn't slide away, agree?
G	Yeah, correct. The pressure is caused by air.
N	That is why when you are walking slowly, the air just slides away. Less friction, less air resistance.
G	Yeah, air pressure... like you are running against something lah, like a brick wall. Punching and pushing a brick wall. Punching will give you faster speed...
N	Direct impact on the wall lah...Let's say if you are running, you are punching...Then if you push, it is very slow, then the brick wall moves, but... Let's say you punch in the center (of the wall), the wall split open, then you feel the impact. But if you push right, the air will just slide away. So there is less air resistance.
	(To parachute question)
N	(Observing the graph) Speed slowly increases, then slows down, because of the parachute.
G	Yeah, slows down. Why the speed slows down? The parachute has more surface area than the person himself.
N	Yeah, than the person alone. The parachute is normally in a curve shape, so it traps air. It becomes like a feather. The man is going down this way, and the air is pushing up this way, so it is like trapping air...Why the speed slows down? It is because...This question is really about falling straight away...or falling flat.
G	Maybe the density...Even you slice a piece of elephant to same area as the feather, the

	elephant will still fall faster.
N	I think it is more trapping of air, you know, Why the speed slows down? Because when the thing opens parachute, the thing spreads open, trapping a lot of air. Not really trapping lah, but having a larger surface area to experience larger air resistance.
G	Yeah, a larger upward force.
N	Then this larger upward force will slow down...
G	Will be almost the same as ...
N	But still less than the downward force, in opposite direction lah. The upward force will be...
G	The resultant force will be downward.
N	So it slows down much more. (Reading) Speed becomes constant?
G	We can explain using terminal velocity.
N	No. This one is after opening parachute.
G	Yeah, it is still the same lah. When you drop a ball, its speed will reach terminal velocity...its speed will be constant.
N	Because you experience a maximum air resistance...after a while, there will be maximum air resistance. Because when you first drop object, the air resistance will be like charging up, so to speak, you know what I mean?
G	Yeah.
N	After a while, there is a maximum air resistance, and the speed is constant. Unusual? Yeah, yeah, this is not really true, because when an object falls down, the speed becomes faster and faster, then it reaches terminal velocity, right?
G	But here you are falling from high place.
N	Yeah, this is falling from really high lah. This is very very high. If you jump from twenty storey you don't expect to reach terminal velocity in ten seconds. So must fall flat before you can reach the ground...
G	Yeah. Maybe if you drop a ball from twenty floor, we can see the speed slowing down.
	(Elephant and feather) why larger air resistance leads to smaller air resistance?
G	You cut down the elephant to the same size of the feather, elephant still has greater mass.
N	Then you have changed to (the situation of) same resistance, because if you put like that, right, resistance would be the same. Let's try the resistance is different.

G	Is it because density is different? Because elephant is much heavier.
	(Iron and wooden ball)
N	This is the same as we cut the elephant to the feather. But this one the mass is bigger. Because mass is bigger, gravitational constant is 10, weight is bigger.
G	So all depends on mass lah.
N	Then we just neglect air resistance lah, so to say, because it is the same, because both are of the same size, so this one falls faster, because it is heavier.
R	Why if there is no air, iron ball is still heavier, but they would fall at same speeds?
G	I got it. The downward force is mg right, acceleration is gravity, is constant. F equals ma, so a equals g.
N	So both would be the same.
G	So we neglect the mass. But if you neglect the mass right, then this one doesn't make any sense.
N	Say in a room with air, iron ball falls faster. Our idea is that because of the weight, the larger weight lah.
G	Yeah, the larger weight.
N	Without air, same size same shape, so they fall at same…
G	Same rate.
N	Yeah, same rate. They will fall at same time.
G	Yeah, same time.
N	Let's try something about energy. Both balls fall at same height, iron, wood. So because of the mass right, iron would have larger potential energy. Potential energy converts to KE, so it can convert to velocity. So this would fall faster.
	Then mgh=1/2mv*v leads to the conclusion of same velocity.
N	Then like that they should fall at same speed.

G	Yeah, mass wouldn't matter.

N	I thought mass is the amount of matter, right. Then in a vacuum without air, no air resistance, they will fall at same speed.
G	Remember last time we are talking about this one, comparing of density between air and piece of elephant skin and feather. The feather is so light that when it drops it doesn't fall at same speed. It is the same as falling of iron and plastic ball in water. We can use something like this lah. Because plastic is lighter than water, so it can float. It doesn't sink like this (iron ball) lah.
R	Are you discussing falling objects in water? I suggest you use iron and stone ball. Both will sink.
N	Yeah. You can't use iron and plastic.
G	Use iron and stone lah.
N	The force is...Weight equals mg...
G	G equals 10.
N	Because g in both situations is the same. If there is no resistance, g is the same.
G	If no resistance, I got it lah. There is nothing...there will be no reaction force...
N	Why the larger downward force falls faster?
G	Ok, iron ball, wooden ball, fall at same rate in vacuum, mass doesn't matter.
N	That is why in a vacuum, right, both would fall at same speed, because g is the same. Then we go to open area with air resistance. Iron ball falls faster. G is still the same, air resistance is same, but weight is different.
G	Yeah. Weight is different because mass is different.
N	Then you say in a vacuum right...do you still have weight in outer space?
G	No no, because there is no gravitational pull.
N	So it falls down very slowly because of no gravitational pull.
N	It is exactly the same thing lah...
G	But this is on earth. That is why the thing can fall down lah...You bring this to a outer space in vacuum...
N	Then it will just float around.

G	Just float.
N	You bring them to vacuum, both will fall at same speed, because g is the same, but why we neglect the weight?
G	We'll come up with acceleration. Now it is speed.
N	Oh, wait. See this is the larger force downward, so with air there will be larger force...
G	Upward.
N	Upward.
G	Ah, I got it. Upward force will be proportional to downward force. The upward force and downward force will be proportional, right.
N	Correct. Let's give it some values.
	1 0.1 10 1 It takes longer for resistance from 1 to 10. So it takes longer to reach terminal velocity.
N	This one has larger resultant force, so it falls faster.
G	Yeah. This one would fall down, still accelerating. It will increase, slowly increase, until this one becomes ten Newton. This one is 9 Newton.
N	This one is 0.9 Newton.
G	Yes. So this one falls faster, so it takes longer to reach terminal velocity.
	Two paper
N	Weight is the same. Surface area will be different. This is almost the same principle as the parachute. This one has more surface area, more resistance.
G	So the proportion will be different. This one will have greater upward force to downward force.
N	This one would achieve terminal velocity...
G	Faster.
N	Faster? Then would not it be...wait...
G	Because the upward force is almost the same as the downward force, right, so it just needs a little time for upward force to gain, then it reaches terminal velocity. The other one would be...because there is less upward force here, the proportion is different, so it takes more

	time to reach terminal velocity.
N	Yeah
	Two Styrofoam
N	It is exactly the same thing lah. Because this has bigger surface area...This one is facing air in this way...right. Same principle lah.
G	Yeah
	Two Styrofoam, different surface area
G	This would be the same. This falls faster.
	G did experiment and
N&G	(Laughing).
G	En, this mustn't happen!
	G did several times more.
N	Let's say this is 10 Newton, the upward force is 1. This surface area is two times.
G	So the upward force would be 2. The proportion is same.
	Two Styrofoam, one thicker
G	Thicker one falls faster. Surface area stays the same, but the mass is...
N	Weight is different.
G	This falls faster.
N	This definitely will fall faster, because air resistance will be the same.

Appendix B: Transcripts for New Study

Legend:

m: Mass	H: Height	V: Velocity	V: Volume	r: Radius
a: Acceleration	g: Gravitational constant (9.8)	D: Density	S: Surface area	

1. Transcripts for the Group of LG & FG

Interview for LG

	(Answering what are the factors that influence falling speed)
LG	They will fall at same speed
R	Are you sure? I give you a coin, and a pen, they will fall at same speed?
LG	Maybe density of the item, and the surface area.
R	Ok, surface area. Any other factors?
	LG can't think of other factors
R	Now talk about elephant and feather. Falling in a vacuum, which falls faster and why?
LG	At the same time. From the book.
	LG unable to explain why.
LG	If I have not learned from my middle school textbook, I think elephant will fall faster in a vacuum.
	Explaining elephant and feather falling in the air
LG	The force that supports the object is larger than the force that supports the elephant.
R	What you mean support?
LG	Pushing up.

R	What you call it? We call it air resistance.
LG	Air resistance.
R	We know supporting force of elephant is larger than supporting force of feather.
LG	I think the support force is relative…The weight of the elephant is so big. It is so heavy, so…
R	You mean relative to weight?
LG	Its surface is larger, but its gravity is also larger

Interview for FG

	Answering what are the factors that influence falling speed
FG	Frictional force and weight of the object. For example, if there is a very sharp object, and it is falling from a certain height, it will move faster than a piece of feather.
R	Ok.
FG	A block falls faster than a feather, because the air…(pausing for a while)
R	En.
FG	The force of the air will influence falling of the paper more than falling of the block.
R	OK.
FG	And the gravitational force will cause them to fall down.
	Answering for elephant and feather which falls faster
FG	Of course the elephant…
R	Why?
FG	The wind has a more obvious effect on the feather because the feather is definitely less in the mass than in the elephant. So the force of wind or air will have…much greater acceleration on the feather than on the elephant…
R	En.
FG	So the elephant will fall faster than the feather.
R	If the elephant has larger surface area and larger resistance, why it falls faster?
FG	But at the same time it has an even greater mass. The acceleration is divided by…is equal to force over mass. So the force on the elephant is very small compared to the force on the feather.

Discussions between LG & FG

Session I

	The Styrofoam and the coin
FG	Of course the coin falls faster
LG	It has smaller surface area
FG	Yes.
R	But it also has smaller weight.
LG	It depends on the air resistance, and air resistance has nothing to do with density.
	After a while
FG	Although the coin has smaller weight, from common sense we know it falls faster
LG	Yes
FG	Then how about the elephant and the feather?
FG	(After a while) I think the elephant falls faster. The acceleration is resistance divided by mass, and the elephant's mass is so big, so that eventually the acceleration is not so big
LG	En.
FG	So the elephant will definitely fall faster than the feather.
	F draws on paper and use formula to explain a=g-Resistance/Mass Resistance/Mass for elephant is smaller
FG	So total acceleration of the elephant will be bigger than total acceleration of the feather.
LG	Yes.
FG	So elephant will fall faster
	Styrofoam, one turned 90 degree
	Easily answered by them: one has less resistance
	Styrofoam, one thicker
FG	The thicker one has the same resistance but larger weight, so it falls faster.
LG	Yes.
	Two Styrofoam, one with larger surface area

FG	Since the one with the twice resistance also has twice the weight, so they will fall at same speed.
	Do experiments and the result is the same

Session II

	Two Styrofoam, one with larger surface area and also thicker
	LG is always using the formula to explain. a=g-Resistance/Mass In this case the thicker one has smaller ratio of resistance/Mass, so it falls faster.
FG	The thicker one falls faster. The density is the same, and the surface area does not influence acceleration.
LG	En.
FG	Only the thickness.
LG	En.
FG	Because if surface area grows two times, the resistance grows two times, and the mass also grows two times.
LG	I think it is four times here.
FG	Yeah, I am considering the area, not the thickness. In this case the thicker one falls faster. You can do experiment
	Do experiment, result confirmed
	Iron ball and wooden ball
FG	Iron ball, larger mass.
	Two iron balls, one larger in size
FG	They are the same. There is a famous experiment done on the tower.
	Since there are no iron balls for them to do experiments, R informs that larger ball falls faster
FG	Why?
FG	Its area and its mass are all related to the radius.
	LG is always using the formula to explain. a=g-Resistance/Mass Here resistance is proportional to square of radius

	And mass is proportional to cubic of radius The result is that the larger iron ball falls faster
LG	The larger one will fall faster
FG	En, so?
LG	Then what about that famous experiment?
FG	Is it the case that in that famous experiment the air resistance is so small that it can be neglected. Its influence on the two balls are not so obvious
LG	En.
FG	Maybe at that time the difference is too small for people to see
LG	I did remember that experiment is wrong

Session III

	Iron ball and wooden ball, the iron ball is larger in size and diameter
FG	Iron ball will fall faster
	L again uses formula to explain a=g-Resistance/Mass So here the iron ball falls faster
	Grouping objects into two groups
	They classify it correctly.
FG	What the high speed objects have in common is that air resistance is quite small compared to its mass.
	Answering did they change their ideas of factor influencing speed
LG	Because at school we are just using formula to calculate, so it is quite different from what we learn from the task
FG	Yes.
	Role of the resistance
FG	It decreases falling speed
LG	Resistance is just one factor influencing falling speed, and mass should also be considered. So we can say resistance influences falling speed, but we can't say resistance determines falling speed

FG	En.

2 Transcripts for the Group of AB & GB

Interview for AB

	What are the factors influencing falling speed?
AB	Surface area and weight.
R	Ok.
AB	Resistance is determined by surface area
	Explaining elephant and feather in vacuum
	AB uses formula to explain F=mg A=F/m=mg/m=g
	Explaining elephant and feather in air
	AB again uses formula to explain F=Weight-Resistance a=F/m=g-Resistance/Mass Elephant has smaller ratio of resistance/Mass, so it falls faster

Interview for GB

	What are the factors influencing falling speed?
	At first of course is the gravitational force.
R	Ok.
GB	Second is the frictional force of the air on the object.

R	We call it air resistance.
GB	Air resistance.
	Explaining elephant and feather in vacuum
GB	They fall at same acceleration g.
R	Why?
GB	Because they are at the same gravitational field.
	Explaining elephant and feather in the air
GB	The feather falls faster because…the feather has small mass but it has larger volume.
R	En.
GB	Shape of the feather…it causes more air resistance than the elephant.
R	Are you sure it has more resistance? Can you imagine, elephant is so big.
GB	Sorry?
R	Can you say the feather has more resistance?
GB	Because it is lighter, so it may change its falling…condition, I mean moving condition easier.
	GB begins to describe the process of reaching terminal velocity: Speed increases, Resistance increases, Acceleration decreases Finally acceleration is zero, and speed becomes constant
R	Ok. But I am asking you why it falls faster if it has larger resistance.
	GB thinks for a while, but unable to provide an explanation

Discussion between AB & GB

Session I

	Elephant and feather
	As the case in the interview, AB again uses formula to explain F=Weight-Resistance a=F/m=g-Resistance/Mass
GB	But elephant has so big surface area.

AB	But comparing with the mass, which is more important? Elephant's surface may be larger than the feather, but the mass is how many times larger.
	AB uses formula to explain Elephant has smaller ratio of resistance/Mass, so it falls faster
	Two Styrofoam, one turned 90 degree
	The one turned falls faster
GB	Yes
AB	Common sense
	Do experiment. Result confirms their prediction
	Two Styrofoam, one thicker
	Do experiment. Not much difference between speed
AB	If you say it is the same, then this contradicts with this (the formula)
GB	As what I say, the thicker one has larger pressure.
	Many futile explanations. Unable to provide reasons.
	Two Styrofoam, one thicker and larger in surface area
	Do experiments. The larger one falls faster
AB	I was considering the thickness increases, and the…
GB	En.
	The surface (at the side) also increases.
	GB uses formula to explain F=Weight-Resistance a=F/m=g-Resistance/Mass
AB	They are of the same mass.
GB	No. no
	AB asks the researcher
R	Judge for yourself
	Then their mass is not the same.
	AB, GB together use formula to explain But unable to know exact value of the different masses

Session II

	Styrofoam and coin
AB	Coin faster
GB	The ratio of the surface to …
AB	To the mass
GB	Yes.
GB	The difference between mass is smaller than the difference between surface
AB	I mean, if this (surface area) is one hundred times of this, and this (mass) is also one hundred times of this, then they will fall at same rate. But this is not the case.
GB	Yes.
AB	You say, this (mass of Styrofoam) is not one hundred time of this one.
GB	Yes
AB	We can then collect one hundred coins and compare.
	Iron ball and wooden ball of same shape and size
AB	Wooden ball, or iron ball…Because…
GB	Iron ball falls….
AB	Iron ball, because it has larger mass.
	Two iron balls, one is larger in size
AB	The little one falls slower
	AB uses formula to explain a=F/m=g-Resistance/Mass Mass is proportional to volume Volume is proportional to cubic of radius Resistance is proportional to surface area Surface area is proportional to square of radius So larger radius means larger acceleration
GB	Depends on the ratio
AB	Yes. If we know the precise value of S/M (surface area divided by mass), then we can decide.

Session III

	Grouping objects into two groups. They have done this correctly
AB	At first I think it depends on the g and air resistance. What is yours?
GB	At first I think it depends on k, the coefficient of friction.
AB	Now my understanding of air resistance is better. I think it depends on the ratio of surface area to mass.
GB	Yes.
AB	I didn't get this formula when I was in the interview
GB	At the interview I was thinking by oneself, and I can't get the spark of…ideas.
	Discussing the role of air resistance in influencing speed.
GB	There are many factors that influence falling speed, including the properties of the object itself. There are many dimensions of the object, including its mass.
AB	Air resistance does not influence falling speed, but surface area influences falling speed.
	Discussing the role of air resistance in influencing speed.
AB	(Using the formula a=g-Resistance/Mass to explain) If it is falling in vacuum, there is no pressure, so this (resistance) is zero, and no matter how big the mass is, g is the same.

3 Transcripts for the Group of SA & FA

Interview for FA

	Answering the case of elephant and feather in the vacuum
FA	They fall at same speed at each moment.
R	Why?
FA	The falls are all due to the gravitational force, and this is the same for all objects.
	Use F=ma=mg/m=g to explain
	Elephant and feather in the air
	Feather (faster). The feather will experience more air resistance.
	After a while.

FA	I think the movement of the feather will be changed more easily than the elephant. And the air resistance...air resistance depends on the speed. Proportional to the speed, I think.
R	Ok.
FA	It is a force that wants to change the movement of the object, according to Newton's first law. We measure whether it is easy to change the movement of the object by the mass of the object.
R	Ok.
FA	Since the mass of the elephant is larger than the feather, it would be harder to change the movement of the feather.
R	Just now you said that feather has larger air resistance, and it has larger surface area. Are you saying this?
FA	Maybe wrong, I think. It is the elephant that occupies larger area.
R	So in this case if the elephant has more resistance, how do you explain the elephant still falls faster?
	FA writes formula on the paper Net force=mg-F (F represents air resistance) a = g--F/m But with formula at hand, still FA is unable to explain.
FA	I don't know how to explain

Interview for SA

	Elephant and feather in the vacuum
SA	Since they are in vacuum, there is no air and there are no other forces to cause it to fall down. The only force on these two subjects are (is) gravity, and gravity equals to mass times g, so the only acceleration is g. Since acceleration is the same, they will fall at the same speed.
	Elephant and feather in the air
SA	Of course the elephant. It has...the mass is bigger compared with the paper?
R	It is feather, feather.

SA	Oh feather. The pressure it makes to the air is greater, according to the mass and volume. Since the elephant gives more pressure to the air, the air will give more pressure to the elephant.
R	Ok
SA	The elephant has more pressure from the air, but compared with its volume and the gravity it has, pressure of the elephant is quite small. When you come to another subject, since the mass is very small, the pressure will influence more than the pressure from the elephant.
R	Ok.
SA	The pressure is proportional to the volume.
	SA begins to calculate on the paper with variables She thinks that resistance is proportional to volume So resistance is proportional to mass/density, and suppose resistance is K * M/D (K: constant, M: mass D: density) a=g-Resistance/M=g-K/D Since elephant has larger density than feather, its acceleration is larger
R	Let me remind you one thing. Just now you are using pressure to refer to air resistance, but it seems to me pressure and force are different things.
SA	Sorry, I think I have used the wrong word.
R	Do you have another common sense way of explaining the situation?
	SA again uses a=g-K/D to explain.
R	You are using Newton's laws. Do you have other ways to explain?
	SA uses energy to explain.
SA	I think when it comes to energy we should also use Newton's laws. We should think about the heat and the gravitational energy.
	After some discussion, SA is unable to produce a new explanation.

Discussions between SA & FA

	Elephant and feather
	SA is using formula to explain
FA	But how come the elephant falls faster if it has larger resistance?
SA	Then we can come to this (the formula).
	SA uses formula to explain, but use it in a strange way F=Weight-Resistance F=G-K* S (G: Gravity, S: surface area, K: constant) F=G-V*K/H (H: height, V: Volume)
FA	Why you consider the volume?
SA	En?
FA	If we have two objects of the same volume, but with different height and surface area. They will fall at different speed. Why you consider the volume?
	A lot of messy discussions, going nowhere
SA	If we cut the elephant to the volume of the feather, then they have different height…
FA	You seem still thinking that they have the same volume?
SA	No, they have different volume. This is one piece of the elephant. We cut this small piece in the shape of the elephant, and the volume of the feather is in the shape of the feather. I can it can be a little clearer if I explain in this way. The shape is the same…
	FA is still confused.
	Iron ball and wooden ball
	They think iron ball falls faster, as it has larger weight.
	Two iron balls, of different size.
FA	The same. According to the experiments done on the famous tower by Galileo
	Some discussions
SA	(After a while) I think they will fall at same time. Since air resistance is proportional to volume. Because it is a sphere, you can cut it in half (from the middle)...
FA	Proportional to...?
SA	To the volume.
FA	Proportional to the volume?
SA	If I know air resistance is proportional to surface area, then these two objects fall at different speed. But...

FA	Because we do not know the exact formula for air resistance.
	SA uses the formula to explain. a=g-Resistance/Mass Here resistance is proportional to square of radius And mass is proportional to cubic of radius The result is that the larger iron ball falls faster
SA	So the result of acceleration is influenced by the R (radius). Can you tell us the answer.
	Researcher tells them the answer: larger iron ball falls faster.
	After some discussion
FA	So we come to the conclusion that acceleration (caused by air resistance) is inversely proportional to R (radius).
	Iron ball and wooden ball of the same shape
SA	I think this is the same as the elephant and the feather.
	Iron ball and wooden ball, iron ball is larger in diameter.
	After some discussions
SA	The iron ball has larger size, and the iron ball has falls faster. Because it has larger density, and it has larger diameter. So the net acceleration experienced by the iron ball is larger than the acceleration experienced by the wooden ball.
FA	En.
SA	Acceleration by air resistance is inverse proportional to density times diameter. Because iron ball has larger density, and it has larger diameter, so its (acceleration by) air resistance is smaller. So the net acceleration experienced by the iron ball is larger than the acceleration experienced by the wooden ball.
	Two Styrofoam, one turned 90 degree: eaily explained
	Two Styrofoam, one thicker.
	They think two falls at the same speed
	Do experiments. Result shows that thicker one falls faster
	SA uses formula to explain. After discussions with FA, she comes to the important conclusion that falling speed is determined by density and height, not surface area.

FA	In this case falling speed is determined by density and height, and surface area does not matter. So thicker one falls faster.
SA	En.
	Two Styrofoam, one thicker and larger
SA	I think the thicker one still falls faster.
FA	Yes.
R	Have you done this question (Two Styrofoam, one with larger surface area)?
SA	We have explained with the equation.
FA	Yeah.
SA	For all the questions, we can use the same formula to determine.
FA	Just change the factors.
SA	Yeah
	Styrofoam and coin
SA	In this question, the height is not given us.
FA	Yeah, what is the ratio between the height of the two objects. Coin falls faster. Maybe Styrofoam has twice height of the coin, but coin's density is much larger than the Styrofoam, not only twice.
	SA and FA engages some discussions of relative height of Styrofoam and coin, and come to the conclusion that they roughly have same height.
	Grouping objects into high speed and low speed
SA	The density of the group that falls with high speed are very big.
FA	Yeah. Some objects like parachute, they not only have small density, but they also have large area.
SA	Yeah, they are very thin, their surface area is very big.
SA	(Later on adds) They are very thin objects, very small height and very big area

4 Transcripts for Discussion between TB & SB

Interview for TB

R	If there is a vacuum, which one will fall faster?
TB	In spite of air resistance, they are the same, according to the famous experiment on that tower.
R	No no...At first we consider there is no air resistance.
TB	No air resistance...
R	In a vacuum.
TB	In a vacuum...They will fall at same speed.
R	Why?
TB	Because of difference between elephant and feather is the mass, but the gravitational acceleration is independent from mass. But in vacuum, I think we can compare with the earth. According to that equation, mass can be omitted on both sides.
R	What is the equation?
TB	This N is the force where the gravitational force comes from. This m can be canceled on both side, This M is constant, So the R and a (acceleration)...When they are falling at the same place, they have the same R, then a (acceleration) is changing. But both a (acceleration) is the same. So they are falling at the same velocities.
R	If they are falling in normal situation with air resistance, what will happen?
TB	Elephant will fall faster
R	elephant...Why
TB	Compared to its mass, and force caused by its mass, the gravitational force it suffered, the air resistance is not so great to influence its falling. But for a feather, the air resistance might be quite large, compared with its mass, its mg.

R	Mg is weight, right.
TB	Yeah, weight. Sorry. Compared with its weight, air resistance is not so large for elephant, but it is quite large for the feather.
R	So...We know elephant has very large air resistance. If it has larger resistance, why it falls faster.
TB	Oh...larger resistance...If we just look at straight above at the elephant...
R	Ok.
TB	If it is falling, we can see the air resistance is large, but every unit of this area, if we make it into many units, every unit of this area, the weight...If the area of every unit is that of the feather, the air resistance must be the same, but the weight of each unit of the elephant must be much much larger than that of the feather. So there is a comparison. Because although elephant's air resistance is larger, its weight is much more larger. The change of the function is not the same. Although from the feather to the elephant, the weight and the resistance are increasing, but they are not increasing at the same pace.

Interview for SB

SB	(Answering in a vacuum why elephant and feather falls at same speed) There is the gravitational constant g, and there is the gravitational force that drags object to the center of earth. And because this feather is in vacuum, so there is no air, there is no resisting force.
R	So if it is falling through air, what will happen? Which falls faster?
SB	Elephant. The density is big. It is a bit like a ball, so the resisting force is not so strong. But the feather…The surface is broad. Therefore it feels the resistance strongly… (pausing) Not like a ball. If you squeeze the feather, it is possible to squeeze the feather (gesturing clumping the feather), they may fall down…at same rate.
R	Just now you are saying that feather falls slower because it has larger air resistance, right.
SB	Yeah.
R	Because it has larger surface area. Its surface area is broad. But we know the elephant is

	very big, so its surface area is bigger than surface of the…
SB	The surface can be relative considering to the weight. For the elephant is very heavy, so even if its surface is very big…I mean the ratio…
R	Ratio between?
SB	The weight and the surface.
R	Why you use this ratio instead of just weight and resistance…Why you use ratio to determine?
SB	If we simply just consider the weight or the resistance...
R	Sorry?
SB	If we simply just consider the weight or the resistance, the answer will not be correct. (pausing for a while) I think if there is a heavy object, and its surface area is very broad, then it will fall at same rate with the feather, but the elephant is…is just like a ball. It can break through the air more easily.

Discussions between TB & SB

Session I

TB	For example, I am taller than you, and my surface area is larger than you. But when I am falling, air resistance is the same.
SB	Then you must consider the weight, and another factor density. If your surface is larger than me, that is weight. But your density is less than me. So you will fall down slower.
SB	Which of the two objects will fall faster? I think the object with larger surface area and lower density…no density does not affect. Surface area…I think the ratio of the weight and surface. For example, in elephant and a feather, although the surface area of the elephant is larger than the feather, its weight is much much more than the feather.
TB	You mean weight over surface area.
SB	I mean this two must be considered together
TB	I agree. Because the weight per area.
TB	The one with larger surface (falls slower). (Comparing two objects at hand: a pen and a piece of paper). Because this (pen's) weight is larger than this, and the surface area of this (the paper) is larger than this one.

SB	So it must fall faster.
TB	Yeah, it must fall faster. But if we have two of the same weight, if these three papers (putting three pieces of paper together) are of the same weight with this one (the pen), this falls faster because the surface of this (the three paper) is larger than this one. The three paper and the ball pen have the same weight, but the surface…This (the three pieces of paper) is quite larger than this one, so the result is obvious.
	Answering what are the factors determining object's falling speed
SB	Do you have an answer?
TB	Weight?
SB	Second reason is weight, the first (is) surface area.
TB	Weight per surface area.
SB	Ok, ok. Elephant and feather…Elephant falls faster, yes?
TB	Because weight per surface area is much larger than the feather.
SB	No no…
TB	It is the ratio…
SB	No no…I think the weight does not affect at all. Because in this question it just asks for air resistance, he is not asking the acceleration of the object.
TB	He is asking why it falls faster. So you must consider the weight.
SB	I mean…I just mean when we talk about air resistance, as long as it has larger surface area, the air resistance should be larger. And then in the elephant it has larger air resistance, but its weight…
TB	This case is the case where elephant will fall faster. So "fall faster" includes two things. One is the force that makes it fall, another is resistance from falling. So both must be considered.
SB	Air resistance is a force or an acceleration?
TB	Force.
SB	Force. So I think for air resistance, as long as it has larger surface area, the force should be stronger.
TB	Yeah, this is true. But the question is why this is the case if…if (inaudible) is just the cause.
SB	Yeah. So I just answered wrongly. It has larger surface area and resistance, but the larger resistance is divided by weight, so the minus acceleration of the elephant will be much less than the feather. So the elephant, we consider the acceleration down there, the minus

	acceleration. So the net (acceleration) is much smaller in magnitude. Acceleration of the elephant will be larger than the feather. It will fall faster.
TB	Force is larger. But a=F/M (acceleration is force divided by mass)?
SB	Can't, the M (mass), yeah. Sorry.

Session II

	Two Styrofoam, one is thicker
TB & SB	(Together) The one turned ninety degree will fall faster.
TB	(Discussing the case of two Styrofoam, one is thicker) You mean this one (thicker one) or this one.
SB	This one (pointing to the thicker one).
TB	If you combine these two (putting the two Styrofoam together to make them even more thicker consisting of three thin Styrofoam), which will fall faster? Faster than this one (the one consisting of two thin Styrofoam) or not?
SB	Yes.
TB	The resistance…the resistance…
SB	the same…The force is the same but the mass is larger.
TB	You remember that experiment on that famous tower?
SB	It is the same. Because at that time, both are iron balls, their resistance is not like this (the case of Styrofoam), they are both (inaudible)... So I think the difference between air resistance can be neglected.
	Iron ball and wooden ball, iron ball larger in size.
SB	(stops for a while and continues) So the iron ball should fall faster absolutely. The iron ball will fall faster than the other iron ball, the iron ball with smaller size and diameter, and that ball with same size and diameter with the wooden ball will fall faster than the wooden ball. It is…
TB	Larger and larger.
SB	Yes.
TB	So this one is larger than this one, and this is larger than this one.

	Two Styrofoam, one surface area twice of the other
TB	Predict.
SB	This one (smaller one) will fall faster.
TB	This one will fall faster.
SB	Let me think…The same, the same.
	Do experiment. Result shows that it is the same
SB	The same. Because the mass…the ratio of the mass and the surface (area).
TB	The larger one can be considered as two smaller one (combined together). So they fall at same speed.
SB	Yeah.
	Two Styrofoam, one surface area twice of the other and also twice thicker
SB	This one will fall faster, although this one's surface area is two times of this one, its mass is four times of this one.
TB	And this velocity (velocity of the smaller one) is equal to one of this (the one with twice surface area), and two (combined vertically) is quicker than one.
SB	Agree.

Session III

	Styrofoam and the coin
TB	Its density is larger than this one.
SB	It is better to say that the ratio of the mass to surface area is (smaller for the Styrofoam).
TB	Yeah, the weight over surface area.
SB	Density is the mass over…divided by volume.
TB	You should also consider thickness.
SB	Oh, so it is not so scientific.
TB	If we have this many coins (covering the Styrofoam with the coin), this will be much heavier than this one, so it will fall faster.
SB	What you mean? Just take one piece of this (Styrofoam) (the same size of the coin), the same as the whole part (its falling speed will be the same as the whole Styrofoam). And it

	(the piece) will fall slower (than coin).
TB	As a whole this will also be slower.

Session IV

	Iron ball and wooden ball, same size
SB	Forces of resistances are the same, but mass of the wooden ball is less, so the acceleration (for wooden ball) is smaller.
TB	So iron ball falls faster.
SB	Yes.
	Iron ball of different size
SB	They are the same…
TB	If they are prefect balls…I think we should calculate, do calculations.
SB	The larger diameter one will fall…
TB	Will fall faster. Our conclusion is bigger iron ball will fall faster than smaller one.

Session V

	Answering the sorting questions
TB	From our life experiences we agree that weight over surface area determines falling speed. TB (after a while): The parachute is for saving lives, so when the parachute is opened, it is very broad. We can see from its shape that it is like an umbrella.
SB	And some air maybe is trapped inside…
TB	Yeah, trapped inside.
SB	If it is flat, it can not be trapped, so…
TB	And the leaves…
SB	Very light, and very broad.
TB	Very broad and very light.
SB	Yeah, the two things (parachute and leave) are the same.
TB	Human being…
SB	It depends on (whether) it falls like this (falling flat), or like this (falling straight).
TB	But like this (falling flat), it is still very fast.
SB	Because its density is very large.

TB	Yeah, density. Because it needs parachute.

Session VI

	Answering the question: does the weight matter?
TB	In a vacuum weight does not matter?
SB	Yes, because there is no air, so no matter what the weight is, no matter what the surface area is, they will fall at same speed. g is acceleration, no resistance.
TB	(Asking SB) What is the role of weight in the case of air?
SB	Exert a gravity force on the body, causes it to fall down at acceleration of g. Weight also plays a role of causing the body to fall down.
TB	In the air, I think weight also plays a role of pushing the object forward.
SB	Yeah, both the same.
TB	And opposite the force of resistance.
SB	I think the role is the same, causing it to fall down.
TB	Air resistance…Weight plays a role of cutting the air.
SB	So it is still causing it to fall down.
TB	Makes the object to collide with the particles.
SB	Acceleration does not only depend on the g, but also on the mass. I still do not think weight matter in the air. Because I think it is the air resistance, not exactly, I mean the root of the difference between speeds of these different objects is the surface area.
TB	I think in a vacuum we always concern g, the gravitational pull, included in weight as a constant. The speed is only concerned with g. But in air…
SB	g is constant no matter what the object is.
TB	I think in our previous explanations we made a tiny mistake. It is not weight over area. It is g over area.
SB	Ah?
TB	g over per area.
SB	No no.
TB	Oh, not the case.
SB	I still think weight does not play a role in the object's falling down.
TB	Then why we suggest weight over area?
SB	Because…Oh I see. The weight in the air…If the weight changes, the air resistance all depends on surface area…Then the air resistance force divided by mass is the minus

	acceleration up. That is how the weight plays a role.
TB	Air resistance plays a role…
SB	I mean because it affects air resistance, acceleration caused by air resistance.
TB	Relatively.
SB	That is how it plays a role.
TB	I think in a vacuum weight still plays a role. It is speeding up.
SB	Both are the same.
TB	So in both vacuum and air, the role (of weight) is the same.
SB	So I think the only difference (of the role of weight) that can be considered as a difference, is the factor…the acceleration caused by air resistance. But actually that is the air resistance that matters, not the weight.
TB	Yeah, both in the air or vacuum the weight plays the same role, all pushing down the object.

5 Transcripts for BG & SG

Interview for SG

R	Ok, it is elephant and feather, if it is falling in vacuum, how will they fall?
SG	In acceleration of g.
R	Why?
SG	Because of gravity. There is a gravity of force on it to draw it to the center of earth. So there is a force, this force will cause the acceleration to cause the feather to fall. Because this feather is in vacuum, so there is no air, and there is no resistance forces.
R	Ok. If it is falling through air, which one will fall faster?
SG	Elephant.
R	Elephant. Why?
SG	Because elephant's density…It is a bit like a ball. So the air's resisting force is not so strong. But the feather's surface is broad, then it is like a…Then the resisting force is strong…It is not like a ball. If you squeeze the feather, then it is possible for it to fall at same speed (with the elephant).

R	Just now you are saying feather has larger resistance?
SG	Pardon?
R	Just now you are saying feather falls slower because it has larger resistance…
SG	Yeah.
R	(Repeating his words) Because it has larger surface area, its surface area is broad. But we know the elephant is very big, so its surface area is bigger than the surface area of the feather…
SG	Surface area is relative, considering the weight. For elephant, it is very heavy, so even if its surface area is very broad, the feather…is very large…I mean the ratio…
R	Ratio between....?
SG	Between the weight and the surface.
R	Why you need to use this ratio instead of using just weight or area…Why the ratio is important?
SG	If we just consider the weight, or the surface area, the answer would not be correct. Because… If it is a very heavy thing, but its surface area is broad enough, I think it will fall slower than the feather. But the feather…But the elephant is…Just like a ball, it can break through the air more easily.
SG	(draws on the paper) If this is an elephant and this is a feather, let's imagine elephant has…the volume of elephant is K, the volume…no the surface of the feather is…because sometimes we can't think the feather has a volume…
SG	(Some deduction on paper to get acceleration) From my experience the elephant will fall faster, but…maybe you can find a strange elephant…
R	Ok.
SG	From experience of course elephant falls faster. But from the formula we can see…if the feather's surface area…Just imagine the feather is like a sword, it has a very…
R	What do you think are the factors that influence falling speed?
SG	Very hard to say. If it is a ball, then it is the volume. But maybe there are things with very strange surface area. So we can't come to conclusion so easily.
R	For Example?
SG	SG draws two objects with same volume but different surface area and shape.
SG	Just like this paper (Grasping a piece of paper) and this disk (holding the CD disk in his

	hand). The disk…When it falls…I don't think it will fall like that…like a paper. There is a volume and mass ratio that causes its movement.
R	Ok, in this case, what are the determining factors?
SG	The two things…If you cut the paper just like that (the CD disk), they will not fall the same.
R	Why elephant falls faster if it has larger resistance?
SG	SG uses formula he has just derived to explain.
R	Ok, I accept your explanation. Do you have some common sense explanation instead of using Newton's laws?
	SG tries for a while but unable to do so.

Interview for BG

R	What do you think are the factors that influence falling speed?
BG	First, for an object, we should know its initial velocity.
R	Ok, let's suppose initial speed is zero.
BG	Then if it is falling in the air, if it is a free fall, then the gravitational constant g will determine the speed of object, and the time will also determine the speed of object.
R	Ok, anything else?
BG	If there is air resistance, the air will also determine speed of the object. (Later on, he asks an interesting question) what is your point for asking this question?
R	(Pausing for a while) I just wanted to know your initial understanding of the question
BG	Initial understanding…
R	Yeah, how you approach the situation.
BG	Because to know the velocity of the object, you must know the initial velocity of the object and its acceleration. If it is a free fall, the gravitational constant determines acceleration of the object. So I think it is like this.
	Elephant and feather falling in vacuum.
BG	Because according to Newton's…The motion in one dimension…According to the formula…Because these two have the same acceleration, because they do not have air resistance in the vacuum.