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Developing Pedagogical Content Knowledge for the New Sciences: The example of biotechnology

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Biotechnology is an expanding area of scientific and community interest, one that it is important students understand because of its potential to impact on them and their communities. The issue for teachers and science and technology educators is how to provide learning experiences in this area. This paper draws on classroom-based research to describe the challenges teachers face and the successes they can achieve when teaching an interdisciplinary subject such as biotechnology. It describes the components of pedagogical content knowledge that teachers require to teach such a subject and highlights planning strategies to enhance teachers' PCK and subsequent classroom interactions. Evidence is provided that biotechnology engages student interest and that students can develop an understanding of the nature of biotechnology and associated conceptual and procedural learning outcomes.

Introduction

The development of scientifically and technologically literate citizens has been almost universally welcomed as a desirable goal for education (Hodson, 2003). However, the relationship between two, like the relationship between science and technology, is complex and evolving. At the beginning of the 20th century the study of natural phenomena was divided into the disciplines of physics, chemistry, and biology; by the end of the century science was viewed as a "transdisciplinary collage of communities of engineers, technologists, scientists and funding agencies" (Latour, 1987, cited in Aikenhead, 2000, p. 246). Modern science research occurs in teams with a focus on the functional aspects of science and technology as it relates to human welfare, economic development, social progress, and the quality of life

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(DeHart Hurd, 1998, p. 409). This shift in emphasis is not as apparent in school curricula (Aikenhead, 2000).

Too often in the past the relationship between science and technology has been viewed in terms of technology as applied science; science and technology as independent communities and or technology as giving rise to scientific understanding (Gardner, 1995). An analysis of both the nature of science and the nature of technology shows that there is a complex relationship between the two. It is therefore important that some of this complexity is apparent in science curricula. Students need an understanding of science and technology and their relationships in order to play an active role as citizens in a democratic society (Hodson, 2003). Internationally, and in New Zealand, many controversial issues have a biotechnological basis; examples include the production and use of genetically modified crops and pharmaceuticals. This article sets out a definition of biotechnology as a discipline new to the New Zealand curriculum, discusses the demands teachers face in implementing biotechnology units, describes the components of pedagogical content knowledge that teachers require to teach such a subject, and highlights strategies to enhance teachers' PCK and subsequent classroom interactions. Evidence is provided that biotechnology engages student interest and that students can develop an understanding of the nature of biotechnology and associated conceptual and procedural learning outcomes.

The Nature of Biotechnology

Biotechnology is usually defined as encompassing the use of living systems, organisms, or parts of organisms to manipulate natural processes in order to develop products, systems, or environments. For example, the *New Zealand Biotechnology Strategy* broadly defines biotechnology as "a group of technologies that are based on applying biological processes to solve problems and make products" (Ministry of Research, Science and Technology, 2003, p. 2). This definition clearly identifies biotechnology as having both scientific and technological dimensions. Consequently, biotechnology education is confined largely to senior science or biology curricula. The New Zealand situation is somewhat different. The reasons for this can be traced back to research and decisions made prior to and during the development of *The New Zealand Curriculum Framework* (Ministry of Education, 1993). At this time there was a strong interest in defining and differentiating "technology" as a discrete learning area, rather than as a subset of science and other disciplines. Subsequently, technology was defined as one of seven compulsory learning areas for Years 1–10 students. Biotechnology is one of the seven technological areas specified in the *Technology in the New Zealand Curriculum* (Ministry of Education, 1995). The implication of this is that biotechnology must be taught to primary and secondary students. For secondary students the positioning of biotechnology in the technology curriculum means that it is likely to be taught by technology teachers with backgrounds in hard and soft materials or food technology rather than science, although there is scope to teach biotechnology within the senior biology and science curricula. The New Zealand situation also differs from that elsewhere in that the definition of biotechnology in the New Zealand technology curriculum includes the need for biotechnological products, systems, and environments to be beneficial to people. This social dimension overlapping with the scientific and technological dimensions presents a challenge for educators.

Teaching Biotechnology Education

There is increasing recognition of the central role of the teacher in reform and appreciation of the complexity of the teaching process and the knowledges that teachers need to deploy in the moment of teaching. It seems that biotechnology is a particularly complex area because of its many dimensions—scientific, technological, sociological, and ethical. This seems to create uncertainties for teachers about how to approach the teaching of this subject, and how to manage students' responses (Michael, Grinyer, & Turner, 1997).

The New Zealand response to the tensions and demands of biotechnology education echoes that described in the international literature (France & Bolstad, 2004). In a recent national study, just over a quarter of the 851 respondent technology teachers indicated biotechnology was not taught in their schools (Jones, Harlow, & Cowie, 2004). Biotechnology was said to be one of the most difficult areas of technology to teach. Teacher knowledge was identified as the most important factor influencing ease of providing technological experiences, particularly for primary teachers.

A number of empirical studies that have explored the characteristics of effective teachers (for example, Gipps, 1999; Wragg, Wragg, Hayes, & Chamberlain, 1998) indicate that effective teachers call on a broad range of knowledge and understandings. Good teacher knowledge of subject content has been found to have a positive effect on decision-making related to changing pedagogical strategies for creating better learning opportunities (Harlen & James, 1997). With familiar content, teachers are able to focus more on levels of student understanding than "mechanical success or failure" (Gess-Newsome, 1999, p. 62). When they move outside their area of content expertise it seems that even teachers with well-developed pedagogical skills experience difficulty in responding appropriately to student thinking. Nevertheless, compartmentalized subject knowledge is not enough. Teachers need a strong overview of relevant subject areas to be able to make the connection needed for effective teaching and learning situations (Carr et al., 2000).

Making sound decisions about what and how to teach, termed by Shulman (1987) as "pedagogical reasoning", requires knowledge of content, general pedagogy, curriculum, learners, educational contexts, and educational ends. Pedagogical content knowledge is the distinctive knowledge of teaching and is a complex blending of pedagogy and subject content, and includes aspects related to an understanding of what is to be taught, learned, and assessed, an understanding of how learners learn, an understanding of ways to facilitate effective learning, and an understanding of how to blend content and pedagogy to organize particular topics for learners (Shulman, 1987). That is, pedagogical content knowledge encompasses useful ways of representing and formulating a subject that makes it comprehensible for others.

Not only do teachers need to understand content and purpose, but they must be able to transform content knowledge so that it becomes pedagogically powerful. Recent studies, for example, those by Cochran, deRuiter, and King (1993), Gess-Newsome (1999), and Magnusson, Krajcik, and Borko (1999), have reiterated that pedagogical content knowledge includes knowledge of subject matter, students, curriculum, and associated pedagogy.

In this paper we explore the dimensions of pedagogical knowledge required for the teaching of biotechnology, a new curriculum area which relies on teachers having an overview and a structure of interrelated ideas so that they are able to make more connections to draw on in teaching and learning situations (Gess-Newsome, 1999).

Connecting with a Sociocultural Framework

This article is based on a sociocultural view of learning where human mental processes are situated within cultural, historical, technological, and institutional settings (Wertsch, 1991). Viewed this way, learning is a situated social process. It is a goal directed activity with cognitive, affective, relational, and conative dimensions that shape and are shaped by the setting (Lave & Wenger, 1991; Salomon, 1993; Wenger, 1998). A sociocultural perspective highlights that learning involves increasingly competent participation in the valued activities of the community of which the learner is a member (Dalton & Tharp, 2002). One critical feature is applying that knowledge in productive action with others (Boaler, 1999). A sociocultural perspective focuses attention on the environment created by the teacher, especially the affordances of the different activities, the nature of the learning community, and the qualities that teachers model (Claxton, 2002). Only if the teacher is present and engaged in activities sufficiently to share the experiences with students will there be sustained, intensive discourse that maximizes learners' development (Dalton & Tharp, 2002). Effective teaching is therefore characterized by the use of meaningful content presented in lifelike situations where learning is enhanced through informed conversation. Assistance from the teacher can take many forms, such as the provision of models to be imitated, the orchestration of tasks and opportunities, practical scaffolding, feedback and guidance, and explicit explanations of principles and procedures (Wells & Claxton, 2002).

Classroom Studies in Biotechnology

In this article we report on the findings of the classroom studies component of a New Zealand Ministry of Research in Science and Technology-funded study aimed at better understanding biotechnology teaching and learning in Years 1–10 classrooms. Building on the work of France (1997) in biotechnology and Jones and Moreland (2003) on teacher pedagogical content knowledge in science and technology, the research was conducted in four schools with sx teachers.

The classroom studies consisted of four phases: a teacher-planning workshop; the collaborative development of classroom materials; classrooms observations, interviews with teachers and students, and the collection of materials used in and or generated through teaching and learning; and the development of case studies of biotechnology classroom practice. The purpose of the teacher-planning workshop was to develop a shared understanding of the nature of biotechnology and the goals of the research. The other purpose was to explore strategies for developing biotechnology ideas into classroom programs. The collaborative development of materials involved the researchers in working with individual teachers to develop unit plans, access materials, develop learning outcomes and activities, and to focus their assessment on biotechnology. While the bulk of the planning was undertaken before the teachers began their teaching, ongoing input from the researchers was required to assist teachers in maintaining a biotechnology focus. Lessons were observed and field notes and photographs taken of students undertaking their work. Relevant documentation was gathered; for example, samples of teacher planning, summaries of teacher-class discussions, samples of student work. Teachers and students were interviewed using semi-structured interviews to ascertain further information about their thinking and learning during the observed lessons (Cohen, Manion, & Morrison, 2000). Case studies of each of the classrooms were developed.

In this article we draw on data from the most successful of the classrooms, that of Jennifer, to present a case of successful teaching and learning in biotechnology and to provide evidence of elements that are critical for success when teachers are struggling to implement a new curriculum area. Jennifer and her Year 8 students worked on a biotechnology unit where the task was to modify traditional fermented drinks over a 3-week period.

The Story of Jennifer's Biotechnology Teaching

Jennifer was an experienced science and technology teacher, although she had not taught biotechnology. She was very conscious of developing ways to assist the children to synthesize the science ideas underpinning their biotechnology task with the hands-on development of a consumer-focused product.

Considering the Nature of Biotechnology and Biotechnological Experiences

For Jennifer, biotechnology is about the manipulation of organisms to produce a product and or to change outcomes. It involves using understandings of biological organisms to manipulate biotechnological variables to develop a product. While Jennifer was not aware of any particular constraints for teaching the unit on fermentation, she was unsure of when to teach the science underpinning the unit and how she would motivate the students to plan their own science experiments without the exercise becoming too teacher-directed. As she said:

> The children lack the experience with science experimentation. They are not keen to plan their own experiments. They can easily follow a recipe but to come up with their own experiment is going to be difficult. It is the same with technology. They are not keen to persevere with their designs. They don't like trying stuff again.

Jennifer identified the importance of teacher knowledges and the role they play in both pedagogical approaches and student learning:

> It would be difficult for a teacher to scaffold a child if they don't really have a deep understanding and experience with the science. Also, knowing what is technology, and what is biotechnology would certainly help and understanding the biotechnological process.

Planning served as a tool for identifying and developing pedagogical content knowledge in support of her confidence and ability to engage with student ideas and actions. Through the planning process Jennifer was able to clarify and develop her own understandings of the nature of biotechnology and the biotechnology involved in fermented drinks. Planning also served as a dynamic tool to ensure she maintained a biotechnology focus in her teaching and to refine her intended student-learning outcomes. Foremost in this process were the considerations: "How is this [activity/action] going to enhance students learning in biotechnology?" "What are the students learning?" This focus was evident in her topic choice, her identification of achievement objectives and learning outcomes, her lesson sequencing and choice of activities, and in her planning for assessment. It was also evident in her interactions with students.

Linking Biotechnology to the New Zealand Curriculum

In her planning, Jennifer identified conceptual, procedural, and societal learning outcomes consistent with the science and technology curricula. Student conceptual learning outcomes related to understanding fermentation; procedural learning outcomes related to the procedures and processes to be undertaken; and societal learning outcomes related to current preferences and the historical background of fermented drinks. Jennifer then derived more specific learning outcomes for individual activities, thus ensuring a close connection between the task, individual activities, and the learning outcomes. She took care to help her students develop the science concepts she deemed significant to their being able to knowledgeably undertake biotechnological modifications.

Also notable in her lesson-sequencing was the inclusion of opportunities for children to build on their ideas and interests. Jennifer kept these in mind as she developed learning activities. She thought about how she would assess throughout the unit, not just at the end, as she was aware of collecting and using information in a formative manner. Planning for this assessment at the pre-teaching stage was important, as this helped her to maintain a biotechnological focus. When she was planning Jennifer also matched her summative assessment with particular learning activities and learning goals, again to maintain the biotechnological balance. The assessment items were recorded beside particular learning goals and centered on biotechnological aspects.

At the end of the unit, Jennifer commented that clarity about the learning outcomes and the science and biotechnology that underpinned these had helped her to focus her interactions on the students' biotechnology learning. She said:

> Having the unit planned in advance in detail was important. We knew where we were going. I really had to be clear about the big picture. Teachers must have a solid understanding of the science behind the technology or I think the learning wouldn't be that meaningful.

Teaching Approaches to Maintain a Focus on Biotechnology

When the unit was implemented in the classroom Jennifer used a variety of pedagogical approaches to ensure that the teaching focus remained biotechnological and that children were afforded the optimum opportunities for developing biotechnological knowledge and understandings whilst still maintaining interest and involvement. These approaches included a strong focus on ensuring children understood the purpose of the task and the activities within it, a focus on the nature of biotechnology, consideration of the influence of the task on children's learning, and ensuring balance between technology and science learning.

Ensuring clear understandings of task and activity purposes. Throughout the sessions Jennifer interacted with the children, helping them understand and meet the purposes of the different activities. Jennifer often wrote the learning intentions for the day's activity on the whiteboard, along with criteria for success. As the learning intentions and the success criteria were clearly established the children understood the purpose of the task and were able to judge how successful they had been. Jennifer's clarity of purpose was communicated to the children, who developed similar clarity. As Tessa (one of her students) commented:

> Teachers should explain everything to students so the students know what they are doing because it will help them learn.

The children understood the task purposes and goals throughout and this meant that they worked towards those goals with less dependence on Jennifer. For example, unbeknown to Jennifer, Group 1 took their modified drink out of the refrigerator earlier than the recipe called for because they did not want it to ferment as much as with the traditional recipe. They then took the modified drink to other teachers in the school to taste test it (the teachers had been their survey target group). They found out that the teachers liked it less fizzy.

Jennifer wanted the children to think about how well they had met the activity and task goals, to help them know whether they had accomplished the goals they had set out to reach. To assist the children with this she included evaluative and reflective activities. The children assessed themselves as to how well they thought they had achieved the stated goals. This meant that they were reflective about the task they had accomplished and had judged their progress. Jennifer expected the children to question themselves and others, give explanations about what they had done and understood, and evaluate their understandings and how well they had undertaken tasks.

Fostering multiple concepts and procedures. Jennifer focused on specific conceptual and procedural aspects in her formative interactions and so opportunities were afforded for the children to develop and use appropriate concepts and procedures. It was evident in the children's conversations and work that they understood the process they had undertaken, understood the need to optimize the conditions for growing yeast, could justify the changes they had made, and understood the need to include the results of their surveys and taste test in their product development. The children were also able to operationalize multiple conceptual and procedural understandings due to their abilities to organize and carry through their ideas by working collaboratively and systematically. The children activated the concepts of fermentation, modification, taste testing, and surveying. This was due to Jennifer's ability to keep the different concepts afloat in the children's minds as well as her ability to help them utilize their understandings in practical ways.

Making connections: focusing on the task as a whole. From the outset Jennifer focused the children on the overall task goal. The modification of a traditional fermented drink to make it healthier and/or more palatable to peers and family was a complex task with a number of components and it was crucial the children appreciated how these fitted together. Without bringing together information from their experience of making a traditional fizzy drink, taste testing, surveying target groups, and experiments to understand the science of fermented drinks, the children would not have known how to apply what was gained from each to the overall task of making a modified fizzy drink. Linking each activity to the task as a whole was very important.

As the children explored the components of the task Jennifer constantly reminded them of how each piece fitted in. Jennifer ensured that the children knew how the goals of the current activity would contribute to the overall task goal. She used a number of strategies to assist with this. For example, she created displays of results from the science experiments about the conditions for yeast, surveys, and taste tests. Strategic decision-making was called for because they needed to work with the constraints of living organism and consumer preferences. For example, Group 1 wanted to use artificial sugar but found that in the science test it did not ferment very well, and they personally didn't like lemon but those surveyed did. Rees said:

> We didn't change the type of sugar even though people wanted it less sweet because different kinds of sugar ferment faster and we added lemon and apple because that's what people wanted even though we didn't like lemon.

Group 2 wanted to make their drink sour because of their taste test results but knew it would affect the fermentation process. John said:

> We wanted to add tartaric acid because people wanted a more sour drink, but we knew it would kill the yeast, so we added it after the drink had fermented.

In order to create a modified palatable fermented drink they had to take into account the findings from all their explorations. They were using their conceptual understandings strategically to optimize the biotechnological outcome.

Developing student understanding of the nature of biotechnology. Jennifer worked to develop the children's understandings about the nature of biotechnology, as well as what it means to undertake biotechnology. Jennifer deliberately provided opportunities for the children to talk about their concept(s) of biotechnology. She began the unit by discussing with the children their concepts of biotechnology and she revisited these several times. This assisted the children to reconstruct and enhance their ideas about biotechnology. She discussed with the children the relationship between the ideas in this particular unit and their general ideas about biotechnology.

Initially, children saw biotechnology as something to do with living things and they mostly related their understandings to the activity they were undertaking. For example:

> I'm not too sure. I know it is making something to help you, cos that's the technology, and the biology part, that's the living things. (Stephanie)

> It's about living organisms and yeast and making fizzy drinks. It's using living organisms to make ginger beer. (Colin)

At the end of the unit the children still saw biotechnology as a combination of biology and technology but now included notions of meeting human needs and bettering lives. For example,

> Bio means living. Technology means making something for a use. If you put them together it means to make something that uses a living organism to help someone or something. (Jenny)

> It is using a living organism to make something. (Colin)

The children had become more confident in their views and developed more comprehensive views of biotechnology as a result of opportunities to discuss their concepts and with involvement in biotechnology tasks. The children considered it was important to build a concept of biotechnology as this assists them to know what they are doing and where they are going. Six of the 31 children advised that teachers should help children understand the concept of biotechnology by making explicit reference to it. For example:

> You should tell the kids what biotechnology is because of they don't know what it means then they will be lost for the whole time you are doing biotechnology. (Kathy)

Orchestrating the interplay of technology and science. Jennifer was very conscious of developing ways to assist the children to integrate the science ideas underpinning the biotechnology task with the technological imperative to develop a consumer-focused product. Jennifer used both "front-end loading" and "need to know" approaches for teaching the science underpinning the biotechnology task. For front-end loaded teaching Jennifer taught the concept that yeast are living in a structured manner in the beginning using a series of science experiments to demonstrate the effects of various amounts of sugar on fermentation. The children then conducted their own science experiments to explore the implications of working with a living organism in a context of their own design. The "need to know" approach was used throughout the unit as Jennifer interacted with the children to build their understandings about yeast in relation to making changes to their drinks.

The technology however, was ever present through the emphasis on modifying a fermented drink on the basis of the survey results, taste tests, and science experiments. Early in the unit the children made a traditional drink, listened to Aunty Gail who shared her stories about making ginger beer in the past, and examined and analyzed commercially made fermented drinks. The purpose of the product analysis was to help the children understand the features of labeling, use of logos, health and safety requirements, and storage features, and for them to think about how different containers can affect the storage of yeast-based products. The purpose of the survey and taste tests was to ensure that the finished product was palatable to potential consumers.

Jennifer was conscious that the biotechnology within the task lay at the intersection of the science and technology concepts and procedures. It was the ability to operationalize the conceptual and procedural understandings they gleaned from many sources which ensured that they were able to complete the task successfully and hence demonstrate an appreciation of the biotechnology

Discussion

A sociocultural perspective on learning and pedagogical content knowledge provides insights into the importance of teachers developing robust pedagogical content knowledge. A review of the literature on teaching, learning, and assessment indicated the importance of pedagogical content knowledge alongside pedagogical knowledge. The emerging sociocultural notions of teaching, learning, and assessment highlight the importance that the culture/discipline plays in teaching and student learning. Drawing from a sociocultural perspective (Stetsenko & Arievitch, 2002), what we know about effective teachers (Dalton & Tharp, 2002), research on pedagogical content knowledge (Gess-Newsome, 1999), and this classroom research, we now argue that pedagogical content knowledge for biotechnology teaching has seven constructs:

- nature of the biotechnology and its characteristics;
- conceptual, procedural, societal, and technical aspects of the subject;
- knowledge of the curriculum, including goals and objectives as well as specific programmes;
- knowledge of student learning in the subject, including existing knowledge, strengths, and weaknesses and progression of student learning;
- specific teaching and assessment practices of the subject (e.g., authentic, holistic, construct reference);
- understanding the role and place of context; and
- classroom environment and management in relation to the subject (e.g., managing resources, equipment, and technical management).

The case study presented here highlights that when teachers have an understanding of the characteristics of the discipline, they develop more secure guidelines for thinking about what is important in the learning activities and the intended learning. For example, Jennifer was able to choose more suitable tasks for developing student learning in biotechnology and could more readily identify biotechnological learning goals on which to base her teaching and assessment practices. By understanding the characteristics of biotechnology and its relationship with and distinctions from science and technology she was better able to audit activities for their biotechnological consistency and connection.

Teachers' development of conceptual and procedural biotechnological knowledge enables them to identify specific learning goals so they can move with more confidence between the characteristics of biotechnology and specific biotechnological learning outcomes. The shift in focus from providing a biotechnology experience to providing opportunities for students to develop particular biotechnological learning outcomes is crucial. Jennifer demonstrated greater confidence with formative interactions, particularly in relation to providing appropriate and descriptive feedback to the children. Direction was given where deemed appropriate, which led to more considered and purposeful interactions. Not only was there more emphasis on providing feedback and assistance to students to develop particular technical skills, there was also more emphasis on conceptual, procedural, and societal aspects.

Teachers need to be aware of what is in national/school curricula and how this relates to biotechnology. For biotechnology as a cross-disciplinary area, it is important that teachers are aware of the relationships between technology, science, and biotechnology, all the more so for primary teachers who are responsible for student learning in all aspects of the curriculum and who are often urged to teach in an integrated manner. Interaction between curriculum knowledge and subject knowledge assists teachers to think about the goals and objectives as well as specific programs for their students. There was a linking between the characteristics of the subject, the specific conceptual and procedural aspects, and the curriculum objectives. This is a transformational process from subject to curriculum to classroom.

Teachers need to be cognizant of their students' conceptual and procedural understandings and how to build on these. Jennifer provided her Year 8 children with biotechnology experiences that stimulated their learning of the conceptual, procedural, technical, and societal aspects. She interacted with the children to help them articulate and justify the decisions they were making about the modification of a fermented drink, encouraging them to develop and use their understanding of the conditions under which yeast live (their science knowledge and technical skills), and the preferences of their consumers (the societal strand of technological development). Jennifer was explicit in her specification of what counts as valid scientific evidence and modeled the skills needed to ensure these criteria were met. Jennifer interacted with students to monitor and provide feedback on their developing thinking and where they might go next.

This case study highlights the challenges and rewards that accrue when teachers are able to attune teaching and learning activities to provide children with experiences that are biotechnological. Jennifer used a variety of ways to explore, develop and focus students' biotechnological thinking (e.g., flow diagrams, demonstration, discussions, illustrating processes and stages) to encourage student reflection, to encourage iteration between different phases, and as a means to look forward. How to effectively teach and assess particular ideas in a subject "is not a solely pedagogical question; it impacts very considerably on the nature of the subject matter" (Barnett & Hodson, 2001, p. 433). Biotechnological learning is also enhanced when students are engaged with authentic activities that are both culturally and personally relevant. In this case, Jennifer selected fermented drinks as an authentic activity to engage the students.

Concluding Comments

Biotechnology is an expanding area of scientific and community interest, one that it is important students understand because of its potential to impact on them and their communities. The challenge for teachers and science and technology educators is how to provide learning experiences in this area. This case study has highlighted the importance of knowing the nature of biotechnology and how both science and technology contribute to it. The article has highlighted some of the characteristics of pedagogical content knowledge that effective teachers call into play to teach biotechnology. These characteristics form a crucial part of teacher education for the new sciences such as biotechnology.

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