EXPLORING THE RELATIONSHIP BETWEEN TEACHER CONTENT KNOWLEDGE AND STUDENT LEARNING

This study explored the relationship between teacher content knowledge and student learning in the context of middle grades force and motion instruction. Recognizing a lack of psychometrically sound measures in this area, we created valid, reliable assessments of teacher and student knowledge through a three-year development cycle. The process involved domain specification, expert review, cognitive interviews with teachers and students, and large-scale piloting and field-testing. In the research study, 25 teachers completed the teacher assessment before teaching a unit on force and motion, then gave the student assessment to their classes ($N = 1,730$ students) immediately before and after the unit. Analysis of the results using hierarchical linear modeling (HLM) suggests a significant and positive relationship between teacher content knowledge and student learning. In addition, the study provides much needed measurement tools for investigating this complex relationship.

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Much preservice and inservice teacher education rests on the premise that teacher content knowledge directly and positively affects both classroom practice and, ultimately, student learning. Researchers and practitioners across the philosophical spectrum generally agree on the necessity of teachers possessing strong subject matter knowledge for effective science instruction. While the premise is logical, empirical support is thin, largely because of a lack of suitable measures. Studies investigating this relationship rely largely on proxy measures of teacher content knowledge, for example certification type (Goldhaber and Brewer, 2000), undergraduate major (Monk, 1994), and courses taken (Druva and Anderson, 1983). Few studies use direct measures of teacher content knowledge.

Teaching is a complex social activity, drawing on teachers’ knowledge, beliefs, and attitudes in ways that are not well understood. There is broad consensus (and some empirical support) for the idea that subject matter knowledge is important; if teachers do not understand the science content, they are unlikely to help students develop understanding, and may in fact do harm. But again, empirical support is thin. There is also widespread agreement on the importance of content-specific knowledge of how to teach subject matter, often referred to as pedagogical content knowledge, or PCK (Shulman, 1986). Unfortunately, PCK has become something of a “Rorschach” phrase, having different meanings for different people. Even less clear is the relationship between PCK, subject matter knowledge, and teacher practice.

The purpose of the study described here was to investigate the relationship between teacher content knowledge and student learning. As part of a larger research project, we created an instrument to measure teacher content knowledge, in particular the knowledge needed to teach ideas in force and motion at the middle grades level. Simultaneously, we created a student assessment for the same content. No such pairs of instruments existed at the time.
Background

An extensive review of research on science teacher knowledge (Abell, 2007) makes the case for the study. Among the findings in this review:

- The literature base on teacher knowledge on the whole is quite thin;
- There is no sense that the research is cumulating; researchers are not building on each other’s work but instead are introducing new constructs related to teacher knowledge and discarding them relatively quickly; and
- The field needs research on the relationship between teacher knowledge and student learning, but is missing the foundational work needed to enable such studies.

Horizon Research, Inc. (HRI) reached similar conclusions in a similarly comprehensive and perhaps more stringent review as part of the MSP Knowledge Management and Dissemination Project (NSF-0445398). The search and selection parameters for this literature review were intended to yield a set of studies with a tight focus on the science content knowledge and pedagogical content knowledge of in-service teachers. To be included, each study had to meet all of the following criteria (Heck, Smith, Taylor, & Dyer, 2007):

- Teachers’ knowledge was studied empirically, through a specific measure (e.g., multiple choice test, open-response written items, interviews) or through systematic analysis of samples of teachers’ work;
- The subjects or participants in the study were practicing in-service teachers within grades pre-Kindergarten through 12; and
- The study was published since 1990.1

The initial search (using both the ERIC and EBSCO databases) yielded just over 1,000 articles on science teacher content knowledge. Close to 90 percent of these were eliminated in an initial screening, in most instances, because the study did not include an objective measure of teacher knowledge. Others were in fact not studies (e.g., they were advocacy pieces) and/or dealt solely with pre-service teachers. The search and screening resulted in 104 studies, the vast majority of which focused on teachers’ subject matter knowledge (e.g., Kruger, 1990; Parker & Heywood, 2000). Only two of the 104 studies directly addressed the relationship between teachers’ science content knowledge and student learning (Magnusson, Borko, Krajcik, and Layman, 1992; Lederman, 1999). In both cases, the findings were mixed. Magnusson et al (1992) found that while teachers’ incorrect ideas tended to surface in their students’ thinking, students of teachers with more correct ideas did not necessarily learn more. Lederman (1999) found no clear relationship between teachers’ and their students’ understanding of the nature of science.

The literature base in mathematics appears to be more robust than in science. In particular, the study described in this paper builds on research about the specialized form of content knowledge

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1 1990 was chosen as a cutoff because of the significant shift in thinking about K–12 science content that occurred at about this time with the beginning of the standards movement, marked by the publication of *Science for All Americans* (AAAS, 1989), *Benchmarks for Science Literacy* (AAAS, 1993), and the *National Science Education Standards* (NRC, 1996).
which teachers hold (Ball, Hill, & Bass, 2005) and relates to studies of teacher content knowledge and student learning in mathematics (e.g., Hill, Rowan, & Ball, 2005).

Method

Instrument Development

The teacher assessment developed and used in this study operationalizes what we mean by teacher content knowledge. Fortunately, the development effort and study were part of a much larger and well-funded project (NSF Grant no. EHR-0335328), which allowed for an elaborate and thorough development process. The process began by identifying the content domain, the idea that an unbalanced force acting on an object changes its speed or direction of motion, or both (American Association for the Advancement of Science/Project 2061, 1993). For research purposes, we further specified the domain by unpacking this idea into 11 “sub-ideas,” which we think of as the smallest assessable grain size of content. We selected a developmentally appropriate subset of these ideas for the student assessment. An expert panel of physicists and physics educators reviewed the content domains for both assessments to insure both accuracy of the ideas and completeness of the unpacking. The content domain is shown in Table 1.

In addition to specifying the science content domain, we specified the kinds of teacher knowledge about the content that we would measure. Knowledge of science content is essential, but we thought it important to measure other types of teacher knowledge as well; e.g., knowledge of misconceptions\(^2\) students are likely to have and knowledge of effective strategies for engaging students with the science content and making sense of the content. After a review of existing literature on pedagogical content knowledge in science (e.g., Carlsen, 1999; Magnusson, Krajcik, & Borko, 1999; Shulman, 1987; Veal and MaKinster, 1999; Wilson & Berne, 1999), we compiled seven content-specific domains of teaching knowledge (see Table 2). We did not expect to develop assessments in each domain but thought the research base in force and motion was extensive enough to support item writing in the following:

- Knowledge of disciplinary content;
- Knowledge/understanding of student thinking about the content; and
- Knowledge of content-specific strategies that move students’ thinking forward.

\(^2\) We use the term “misconception” from here on to describe anything that precedes full understanding of a specific idea. Some misconceptions may represent important steps in a progression toward full understanding.
Table 1.
Content Domain for Teacher and Student Assessments

<table>
<thead>
<tr>
<th>Sub-Idea</th>
<th>Sub-Idea Description</th>
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<tbody>
<tr>
<td>A†b</td>
<td>A force is a push or pull interaction between two objects, and has both magnitude and direction.</td>
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</table>
| B†       | All of the forces acting on an object combine through vector addition into a net force; they either balance each other out (net force is zero), or act like an unbalanced force (net force is not zero).  
  • If the sum of forces exerted on an object in one direction is the same strength as the sum of forces exerted on the object in the opposite direction, then the forces on the object are balanced (i.e., the net force is zero).  
  • If the sum of forces exerted on an object in one direction is greater than the sum of forces exerted on the object in the opposite direction, then the forces on the object are unbalanced (i.e., the net force is not zero). |
| C        | A force diagram uses arrows to represent the forces acting on an object at a particular moment. The length of the arrow represents the relative magnitude of the force. The direction of the arrow represents the direction of the force acting on the object. |
| D†       | If an object is moving faster and faster, then there is a net force acting on the object in the same direction as the motion. |
| E†       | If an object is moving slower and slower, then there is a net force acting on the object in the direction opposite to the object’s motion. |
| Fc       | If an unbalanced force acts on a moving object in a direction that is neither in the direction of the object’s motion, nor directly opposed to it, then the object’s direction (and possibly speed) will change. |
| G        | If there is an unbalanced force acting on an object, the greater the strength of the unbalanced force, the greater the change in the object’s velocity. |
| H        | If there is an unbalanced force acting on an object, the more massive an object is, the smaller the change in the object’s velocity. |
| I†       | If an object has constant speed in a straight line (or zero speed), then there is no net force acting on the object. This can occur either when:  
  • the forces on the object are balanced; or  
  • there are no forces exerted on the object. |
| J†       | The force of friction acts to oppose the relative motion of two objects in contact. Friction acts on both objects along the surfaces in contact with each other. The magnitude of friction depends upon the properties of the surfaces and how hard the objects are pushed together. |

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b †Denotes sub-ideas considered part of the student domain.  
c This sub-idea is included for completeness of unpacking only. It is not assessed.
Table 2.
*Hypothesized Content-Specific Domains of Teacher Knowledge*

<table>
<thead>
<tr>
<th>Domain Name</th>
<th>Brief Description</th>
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<tbody>
<tr>
<td>1. Knowledge of disciplinary content</td>
<td>This knowledge refers strictly to the science content, with no other elements of what a teacher would need to know in order to relate the content to students.</td>
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<tr>
<td>2. Knowledge that alternative frameworks for thinking about the content exist</td>
<td>When teachers have deep knowledge of disciplinary content and recognize that different ways of organizing ideas exist, they can focus on helping students understand the important ideas, without necessarily requiring students to organize ideas in the exact same way. Such knowledge also enables teachers to recognize student understanding that is correct, but presented differently from how the teacher might organize it.</td>
</tr>
<tr>
<td>3. Knowledge of the relationships between big ideas and the supporting ideas in a content area</td>
<td>Teachers need to help students avoid being so focused on the small details of the content that they never grasp the larger (and more powerful) concept.</td>
</tr>
<tr>
<td>4. Knowledge/understanding of student thinking about the content</td>
<td>To help students understand content, teachers need to know what ideas students are likely to bring with them and where they are likely to struggle. Some content areas—e.g., force and motion—have a rich research base on student preconceptions and misconceptions, which includes research on how resistant these ideas may be to change. Most content areas do not have such a research base.</td>
</tr>
<tr>
<td>5. Knowledge of strategies to diagnose the thinking of a particular group of students</td>
<td>Teachers need to know how to discern what ideas students have about a content area, both prior to and during a unit of instruction.</td>
</tr>
<tr>
<td>6. Knowledge of how to sequence ideas for students to learn the content of interest</td>
<td>This type of knowledge highlights one of the differences in how a teacher and scientist think about content. A teacher needs to be able to think about content in terms of how students can most efficiently come to understand it. They need to know which ideas are pre-requisites for later ideas and how to progress from less complex to more complex ideas.</td>
</tr>
<tr>
<td>7. Knowledge of content-specific strategies that move students’ thinking forward</td>
<td>In addition to knowledge of student thinking, teachers need knowledge of ways to move that thinking forward. Included in this knowledge is an awareness that not all strategies will work equally well with all groups of students. The implications of some student differences are obvious—e.g., seeing or hearing impairments. Others are more subtle; e.g., representations that communicate well for students in inner city settings may not work well for students in rural schools, and vice-versa.</td>
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</tbody>
</table>

To get at knowledge of student thinking, we wrote items along the lines of: “Which of the following misconceptions are students likely to exhibit in a study of force and motion?” While the research base in force and motion has identified prevalent misconceptions, it is not strong enough to argue the relative prominence of two misconceptions. Further, it seemed unreasonable to expect teachers to be thoroughly familiar with the literature on student thinking in each content area they teach.
Multiple-choice items testing teachers’ knowledge of instructional strategies were abandoned on different grounds. After many attempts to write such items, we recognized that even in force and motion, the literature is not strong enough to judge the relative effectiveness of two or more activities that reasonably address the same idea. Rather, such items tended to reveal teachers’ beliefs or attitudes more than their knowledge. Teachers sometimes chose a hands-on activity over a lecture or reading, simply because the activity was described as hands-on. Attitudes and beliefs are important determinants of instruction, but the focus of our study was teacher knowledge.

Based on these experiences, we limited our assessment items to content knowledge. Ultimately, we identified three types of items for the teacher assessment, each set in instructional contexts:

1. knowledge of science content;
2. ability to use content knowledge to analyze/diagnose student thinking; and
3. ability to use content knowledge to make instructional decisions.

To enable large-scale research, we set out to create a tool that would be minimally burdensome, for both the test taker and the researcher. Accordingly, we opted for a multiple-choice format, even though such items have limitations. Well-constructed open-ended items may probe more depth of understanding, but they are more burdensome for both the researcher (in terms of scoring costs) and the test taker (in terms of time required to complete the assessment). In addition, scoring open-ended items requires the training of raters to establish inter-rater reliability.

We began developing our multiple-choice items by first asking approximately 100 teachers to respond to open-ended items about the teaching of force and motion concepts. A sample item is shown in Figure 1. We accomplished two things through these items. First, responses gave us a window onto teachers’ thinking about the content, in many cases revealing the kinds of misconceptions teachers have about force and motion. (In most instances, their misconceptions were the same as those identified in the literature as being held by middle grades students.) Second, we used their responses to generate distractors for the multiple-choice items.
At the beginning of a unit on forces and motion, you set up a demonstration for your students, in which a rubber band, stretched between two posts, is used to launch a toy car across the classroom floor.

Following the demonstration, you ask the students to explain the forces acting on the car just after the car is released from the rubber band. Students are likely to offer a number of different answers, some correct and some incorrect.

What are some incorrect answers your students are likely to give? For each incorrect idea, please explain why you think a student might have that idea.

What would be a completely correct student answer?

Figure 1. A sample open-ended item for teachers.

Examples of each item type (knowledge of content, using content to analyze student thinking, and using content to make instructional decisions) appear in Figures 2 – 4. The correct answer in each item appears in bold text. Note that in Figures 3 and 4, only one answer choice is correct in terms of the science and in terms of the student thinking displayed.
A teacher gives her students the following question on an end-of-unit test.

**Student Assessment Item**

A boy slides a salt shaker along a table toward the right. As the salt shaker slides, in which direction does the force of friction act on the salt shaker?

What would be the correct answer?

A. To the right  
B. **To the left**  
C. Upward  
D. Downward

Figure 2. *Example of an item assessing knowledge of science content.*

A teacher asks her students to identify whether the forces acting on a car accelerating onto the highway are balanced or unbalanced. The majority of students agree that the forces acting on the car are unbalanced.

Which of the following is the best assessment of these students’ response?

A. Because an increasing net force is required to make an object move faster and faster, the students *correctly* identified the forces on the car as being unbalanced.  
B. Because a non-zero net force is required for any type of motion, the students *correctly* identified the forces on the car as being unbalanced.  
C. **Because a non-zero net force is required to make an object move faster and faster, the students *correctly* identified the forces on the car as being unbalanced.**  
D. Because friction always acts to oppose motion and balances the forward force on the car, the students *incorrectly* identified the forces acting on the car as unbalanced.

Figure 3. *Example of an item assessing teachers’ ability to use content knowledge to analyze student thinking.*
The question below is administered to a group of middle school students.

Student Assessment Item

A fan is attached to a cart. The fan is turned on and the cart begins to move along the track. Friction and air resistance are small enough to be ignored. What will happen to the cart after it starts moving?

If a majority of students predict that the cart will keep moving at a constant speed, which one of the following would be a good next step in the development of these students’ understanding of the effect of a constant non-zero net force on motion?

A. Reinforce the concept by asking a similar question but in a different context.
B. Have students experiment by adding different size masses to the cart.
C. Demonstrate for students what happens when a constant non-zero net force is applied.
D. Introduce students to the concept of how a changing force affects an object’s acceleration.

Figure 4. Example of an item assessing teachers’ ability to use content knowledge to make instructional decisions.

We then undertook a months-long iterative process of conducting cognitive interviews with more than 50 middle grades teachers and revising items based on teacher feedback. The protocol is shown in Figure 5. A pool of 60 multiple choice items was then piloted with approximately 1,500 physics/physical science teachers (1,200 middle grades and 300 high school) in spring 2005. The high school teachers were included to ensure that we would have some respondents at the upper end of the knowledge spectrum.
### Prologue:
We are developing a test for middle school teachers who teach physical science, and we need your help to make sure the questions are asking what we think they are. The point of this interview is to help us write a good test, not to test what you do or don’t know. Do you have any questions before we get started? Remember that all of your answers are confidential.

### Procedure:
- Ask teacher to read aloud and “think aloud” as they read the questions and answer choices, if they are comfortable doing so.
- For each multiple choice item, ask:
  1. Why did you choose that answer? (probe for words or diagrams they keyed in on, as well as their thinking behind the response)
  2. Were there other answer choices that you almost chose? (why?)
  3. Were there any answer choices that you did not even consider? (why?)
  4. Was there an answer choice you were expecting to see, but did not? What was it?
  5. Were there any words or diagrams you did not really understand, or situations that made the question confusing?
  6. Do you have any other comments on the item?

Figure 5. Cognitive interview protocol for teacher assessment items.

We used item response theory (IRT) as our psychometric framework (see for example, Swaminathan, Rogers, & Hambleton, 1991). Using BILOG-MG 3.0 (Zimowski, Muraki, Mislevy, & Bock, 2003), we estimated the discrimination parameters (how well each item discriminated among teachers of varying knowledge levels) and difficulty parameters (where in the knowledge spectrum each item provided the most information) for all the items. Based on these, we chose a subset of 33 items to field test with 750 teachers, again with roughly a fifth of the sample being high school teachers. Items that did not discriminate well (i.e., provided little information about teachers’ knowledge) were dropped. Dimensionality analyses of the pilot and field test data, consisting of both factor and cluster analyses, indicated a single dominant trait was being measured by the items. We termed this trait “content knowledge for teaching.” Ultimately, we created a teacher assessment with 25 multiple-choice items. The group of items has an internal reliability of 0.84.

The development process is depicted graphically in Figure 6.
We employed a similar process in developing the student assessment. The conceptualization was more straightforward, as we sought to measure only content knowledge. This measure also had 25 multiple-choice items, forming a unidimensional scale with an internal reliability of 0.86.
Study Design

As described above, this study focused on the relationship between teacher knowledge in force and motion, as measured by our teacher assessment, and student learning, as measured by our student assessment. We hypothesized that student learning would be greater when students had teachers with more understanding of force and motion ideas.

In the summer of 2006, we administered the force and motion teacher assessment to 60 9th grade physical science teachers taking part in a teacher enhancement project. The teachers received no formal instruction on force and motion after completing the assessment. During the 2006-07 school year, these same teachers (N = 60) were invited to administer our force and motion student assessment to their classes immediately before and after a unit of instruction on force and motion. The study addressed two research questions:

1. Do students score higher on the assessment following instruction, and if so, what is the size of the change?
2. Assuming a significant change in student scores exists, is there a relationship between this change and scores on the teacher assessment?

Data Collection

Teachers completed the assessment at one of their summer workshop sessions. During the following school year, teachers administered the student pre- and post-test to each of their classes. Twenty-five teachers returned completed materials, representing 1,730 students. While the teacher response rate is low (42 percent), there were enough teachers and sufficient variation in their scores to justify analyzing the student assessment scores in relation to the teacher scores. Within these teachers’ classes, the student response rate was essentially 100 percent.

Analysis and Findings

Because of the potential for covariation in scores among students in the same class, we used a three-level hierarchal linear model (HLM) (Bryk & Raudenbush, 2002) to examine the relationship between student gains and teacher content knowledge. Time-points (pre- and post-test) were nested within students, and students were nested within teachers. The results of the analysis are shown in Tables 3 and 4.

The analysis found that the post-test student assessment scores were significantly different than the pre-test scores (HLM, p < 0.05), with an effect size of 0.84 standard deviations. In addition, the analysis found a statistically significant relationship between teacher knowledge, as measured by the teacher assessment, and the student post-test scores on the student assessment (HLM, p < 0.05), an effect of 0.19 standard deviations. In other words, one would expect students of a teacher scoring one standard deviation above the average on the teacher assessment to score 0.19 standard deviations greater on the post-test than students of a teacher with the average score on the teacher assessment.
The relationship between teacher knowledge and student learning may be only correlational. For instance, it may be that more knowledgeable teachers simply teach more knowledgeable students. However, the analysis found no significant relationship between teacher knowledge, and the pre-test scores on the student assessment. Obviously, teacher knowledge cannot directly affect student learning, but this study lends support to the argument that teacher knowledge plays an important role in student learning, most likely through the mediating variable of classroom instruction.

Table 3.
Regression Coefficients and Standard Errors

<table>
<thead>
<tr>
<th>Fixed Effects</th>
<th>Coefficient</th>
<th>se</th>
</tr>
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<tbody>
<tr>
<td>Intercept</td>
<td>48.63*</td>
<td>1.76</td>
</tr>
<tr>
<td>Time-points Characteristics (level 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>18.91*</td>
<td>1.48</td>
</tr>
<tr>
<td>Teacher Characteristics (level 3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teacher Assessment Score</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Teacher Assessment Score * Post</td>
<td>0.23*</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* p < 0.05

Table 4.
Student Predicted Scores

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Predicted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Force &amp; Motion Score*†</td>
<td></td>
</tr>
<tr>
<td>Pre-score with average teacher</td>
<td>48.63</td>
</tr>
<tr>
<td>Post-score with average teacher</td>
<td>67.54</td>
</tr>
<tr>
<td>Post-score with teacher one std deviation below</td>
<td>63.50</td>
</tr>
<tr>
<td>Post-score with teacher one std deviation above</td>
<td>71.58</td>
</tr>
</tbody>
</table>

* The post-test scores are significantly different from the pre-test scores (HLM, p < 0.05; effect size of 0.84 standard deviations).
† The analyses found a statistically significant relationship between teacher knowledge (as measured by the teacher assessment) and the post-scores in student assessment scores (HLM, p < 0.05; effect size of 0.19 standard deviations).

Conclusions

This study did not collect data on instruction, and clearly, as mentioned above, many other factors besides teacher knowledge affect student learning. In this study for instance, the project provided all teachers with instructional materials for teaching a unit on force and motion, which included many educative components for the teachers. We suspect that the materials compensated for some gaps in teacher content knowledge. If so, then this study probably underestimates the relationship between teacher knowledge and student learning.

The study also suggests the research strategy employed is promising. The approach consisted of identifying a narrow content area of interest, then developing teacher and student assessments aligned to the content but appropriate for each audience. That is, we did not simply administer a
student assessment to teachers to measure teacher knowledge. Not only would such an approach be potentially demeaning to teachers; it might not be sensitive to the particular ways in which teachers use content knowledge in their work.

In summary, this study contributes to the field in three ways. First, the instrument development process itself and the resulting measures provide insight into what types of teacher knowledge are measurable and, specifically, what types are measurable in a multiple-choice format. Our instrument measures teachers’ knowledge of force and motion ideas and teachers’ ability to apply that knowledge to instructional decision making. Second, the work provides the research community with rigorously constructed, valid, reliable, minimally burdensome tools to use in studying the relationship between teacher content knowledge and student learning. Finally, the study provides evidence for the claim that teacher content knowledge positively correlates with student learning. In short, this study strengthens a weak research base through both its findings and the tools it developed.

The author would like to acknowledge the National Science Foundation for funding under Grant no. EHR 0335328. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the National Science Foundation.

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