The CryptoClub

Developing a Middle-Grade Mathematics Program for Afterschool

Janet Beissinger, Bonnie Saunders, Rodney Harris and Gail Tang
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In a CryptoClub afterschool program, middle-grade students explore cryptography while applying mathematics to make and break secret codes. The playfulness and mystery of the subject is engaging to students, and the afterschool environment allows them to learn at their own pace. They encrypt, decrypt, and crack messages using mathematical ciphers that have been used by cryptographers and they learn about the colorful history of cryptography. Students practice with games and challenges, and along the way they develop their mathematics, reading, and vocabulary skills.

With so much emphasis on high-stakes testing, teachers have less time during the school day for activities that are not directly related to these assessments (Walker, Wahl, & Rivas, 2005; Miller, 2003). The afterschool environment provides the opportunity to explore additional enriching topics and provide learning experiences that are different from, but supportive of, those offered in a normal school day (Schwartz&Noam, 2007). CryptoClub is an example of how the afterschool environment can be successfully used to focus on an interesting and relevant STEM[1] topic from outside the regular school curriculum, while applying topics that are within the school curriculum.

The CryptoClub Project at the University of Illinois at Chicago is in the third year of a five-year National Science Foundation grant to develop and test cryptography curricular material for afterschool and online use. The nature of afterschool programs requires that the material be flexible enough to appeal to a broad range of students and to meet the needs of leaders in different types of programs. Therefore, our project design involves gathering input from leaders and students in afterschool programs held in different kinds of informal educational settings throughout the development stages. Over the course of the grant, we are working with a variety of afterschool program leaders, including middle-grade teachers, leaders who train college and high school students to lead programs in schools and community centers, museum educators, and mathematicians who lead "Math Circles" for enrichment. As we develop the curriculum, we will also draw from the CryptoClub staff's experience in presenting cryptography in other settings: university outreach programs for middle-grade students, teacher preparation courses for pre-service middle-school teachers, and courses for math majors.

To date, we have observed programs, interviewed students, and surveyed leaders to gain insight into how students and teachers engage with the cryptography materials. Our aim has been to learn which activities are engaging, as well as what challenges leaders face in implementing the program. Data from these sources has informed revisions and ongoing development of the cryptography curriculum.

[1] Science, Technology, Engineering, and Mathematics

In this paper, we reflect on the development of our materials, so far, and on lessons we have learned about designing STEM activities and materials for use in informal educational settings.

Overview of the CryptoClub Project

History of the CryptoClub

Our project's involvement in the afterschool setting grew out of earlier work that resulted in a middle-grade cryptography textbook for classroom use, authored by mathematicians (Beissinger & Pless, 2006). The teachers that pilot-tested the textbook confirmed that children's natural interest in secret messages, combined with the mathematical nature of the subject, make cryptography a motivating setting for learning and applying mathematical skills. But several reported that it was difficult to find time to teach an extra subject in the already crowded school day so they offered cryptography in afterschool clubs. We learned from their afterschool trials that the informal afterschool setting had benefits and challenges that were different from those in the regular classroom setting. Thus, the CryptoClub Afterschool Project was created to design material specifically for afterschool use that would take advantage of the benefits and address the challenges of this setting.

What Happens at a CryptoClub Afterschool Program?

A CryptoClub program consists of about 20 one-hour sessions. During a typical session, students are introduced to a cipher (method of encrypting), and then practice it through games and activities that involve sending and receiving secret messages. Some activities involve moving around, for example, students might engage in a treasure hunt, following a trail of encrypted clues around the school, or in a relay race with teams running back and forth, competing to be the first team to gather and decrypt the parts of a secret message. Other activities involve sitting more quietly and thinking deeply about patterns that might help break a code.

Although CryptoClub activities are playful, the mathematics involved is significant. As students send and crack messages, they apply topics that are in the regular middle-grade mathematics curriculum. Those topics include negative numbers, decimals, percents, prime numbers, factorization, common factors, multiplicative inverses, division with remainder, exponents, clock arithmetic, and pattern recognition.

"Cracking" messages leads students to explore their own ideas about cryptography and mathematics. On the first day they are usually invited to crack the encrypted answer to a riddle such as the one in Figure 1. Working together, a group of middle children will not only discover the answer[2], but they will usually notice the pattern in the cipher: each encrypted letter is just the next in the alphabet. They are well on their way to understanding the Caesar "shift" ciphers, which can eventually involve addition, subtraction, and negative numbers.

[2] Answer: a bumbling bee

Later, more complex mathematics can be approached in the same way. Students crack a number cipher used to encrypt seven words (Figure 2). They notice that each line ends with the same three numbers, so each word must end the same way. Someone usually guesses that the days of the week are encrypted. By considering word length and letter patterns, students figure out the letters in each word. Now they are ready to figure out what cipher was used, so they start a cipher table (Figure 3). Students usually notice the patterns of repeated addition in the table. By the time they discover the peculiar multiplicative patterns, they are prepared to explore multiplication with modular (clock) arithmetic.

Materials and Professional Development

Previously, there were few resources for leaders to teach cryptography to middle-grade students, particularly in informal settings. Although it is related to the middle-school curriculum and a valuable way to practice middle-grade skills, the topic is not usually taught at this level. Furthermore, afterschool leaders do not usually have the time or expertise to develop their own material. Consequently, to support afterschool CryptoClub programs, we are developing and testing a student *Cipher Handbook* and an afterschool *Leader Manual*, as well as an interactive website for use by students and teachers. We also offer three-day workshops to train leaders of CryptoClub afterschool programs.

Student Cipher Handbook

The *Cipher Handbook* has content similar to that of our previously published book (Beissinger & Pless, 2006), but in a format designed for informal programs. The handbook presents key ideas in summary form at the top of each page with a brief example, followed by short practice. The format is intended to enable quick introduction of new material and to serve as a reference for students as they engage in activities of the club. This format also helps students who were absent from a previous CryptoClub session to make up what they missed. The *Cipher Handbook* gathers all content in one place, rather than in a collection of handouts that are provided session-by-session. We have observed the handbook effectively being used in action. For example, in a treasure hunt, students carried their handbooks with them around the school and quickly looked up details when needed.

Leader Manual

The *Leader Manual* gives suggestions for introducing material and descriptions of games that apply it. It also has pages that provide additional messages to use with games and to extend the material. The *Leader Manual* is designed to provide flexibility for leaders to create their own messages with themes that are of interest to their students. But if time is limited, leaders can choose from a supply of encrypted messages that require no extra work. The *Leader Manual* also discusses common student errors and connections to the mathematics of middle school.

Online Activities

A main focus of the CryptoClub Project, in addition to developing materials for site-based CryptoClubs, is the development of a collection of online cryptography-related

games and challenges. Features developed so far include an online treasure hunt with encrypted clues, computer tools that help users encrypt and decrypt their own messages, a collection of sample messages to crack, and a graphic novel based on historical events that involved cryptography. Findings from preliminary testing of website activities with students suggest that, as this site is launched and developed, it will be a valuable resource for CryptoClub students to continue learning about cryptography outside their afterschool program. We also expect that the website will attract a community of users who want to learn about and experience cryptography on their own.

Online Cryptography Tools for Teachers
We are also developing online tools that will help teachers prepare activities for their students. Teachers can use the encrypting/decrypting tools of the CryptoClub Website site to prepare and print encrypted messages for their class. They can also post encrypted messages on a private message board that is accessible only to their students. To help teachers with the time-consuming task of designing a treasure hunt, we are developing an online clue generator that will help teachers create, encrypt, format, and print clues of their own.

Leader Training Workshops
Since cryptography is a topic that is new to most teachers and afterschool leaders, we offer three-day leader-training workshops. While cryptography is an engaging way of practicing middle-school mathematics, it usually does not appear in middle-school curricula and therefore may require special training, even for teachers. Our workshops provide background in content, while giving leaders a chance to experience some of the games and activities, and discuss issues of leading a program. The workshops can benefit leaders who are unfamiliar with the content, but experienced in how children learn, as well as those who are knowledgeable about cryptography, but unfamiliar with middle-grade curriculum or activities suitable for teaching in informal settings.

Research and Development

Ongoing research by our project staff has been invaluable in guiding the development and revisions of the Cryptoclub curriculum materials. During the first two years of the project our research has focused on the following questions:

- What types of activities do students enjoy while learning cryptography in the afterschool environment?
- What challenges do leaders face in implementing a cryptography program in afterschool?
- How can materials be designed to meet the challenges and support the learning of cryptography and mathematics in afterschool?

Our research in the first three years has been designed primarily to inform the development of materials. We began with a pre-pilot year in which we worked closely with leaders and students from just one program as we developed and tried out activities. We are now in the second of two pilot years in which several leaders test drafts of new material. Our fourth year will be a national field test, in which a near-complete set of

materials will be tested with a wide audience. An independent research organization is conducting the project evaluation, and will collect and analyze data during the field test.

Early Development: Pre-pilot Phase
During the first year (2009), we worked closely with staff at Chicago's Young People's Project (YPP). The YPP is a national organization that uses mathematics literacy as a tool for social and educational change. They implement a 3-tiered model in which college students are trained to instruct high school students to lead math activities with younger students in afterschool programs. This organization has a history of leading math programs in afterschool settings, particularly in African American and Latino neighborhoods. We collaborated with YPP instructors during the early design of the curriculum so we could create material suitable for the learning styles and interests of students from these groups, which are underrepresented in the mathematics field.

UIC developers met regularly to train YPP instructors in cryptography and to help them plan for each student session. YPP instructors taught most student sessions, but some were taught by UIC developers. This helped instructors see the greater potential of the materials and allowed developers to experience first-hand the strengths and weaknesses of the activities. UIC researchers observed nearly every YPP session and CryptoClub staff debriefed regularly to brainstorm ways to improve the program design and material.

Initially, instructors used material from the original CryptoClub textbook (Beissinger, Pless, 2006). YPP instructors and high school students helped us to see ways to adapt that material for afterschool use. Although the high school students were being trained to teach, they were, in fact, first-time learners of cryptography, and their reactions and reflections on their learning experience were helpful. Students gave advice on the kinds of new activities we needed to create:

> "It's fun being competitive because it makes you work faster at it."

> "Have us moving because it's like, we're all day sitting down at school. We want a program that's going to make it fun. Make us forget about school for a while."

We responded with new activities such as a relay race that involved decrypting messages. Students let us know we were on the right track. This student quote sums up the group's reaction after the race: "I think we should have a lot more of what we just did."

When interviewed at the end of the session, the YPP high school students cited games as among their favorites and they suggested that we develop more competitive activities. They liked the playfulness of our games, and also commented that they liked the challenge of games that made them think.

Our first-year experiences informed us of some of the difficulties of running an afterschool program. Student attendance was highly variable and appropriate classroom space was often not available. We saw students enjoying the fun activities, but we were disappointed that the program did not go deeper into content. Although discouraged, we also knew that we had provided inadequate student materials and leader training. What

we learned that year gave the foundation for the *Cipher Handbook*. Experience we gained training YPP instructors helped us design the leader-training workshop to prepare new leaders the following year.

Pilot Phase
In the second year (2010), we began a pilot test of the program on a wider scale. We added a group of 13 elementary school teachers from 11 schools in the Chicago area, while continuing to work with the Chicago YPP. In 2011, we added YPP CryptoClubs in Michigan, Mississippi, and California, as well as more teacher-led programs in the Chicago area.

Teachers from a variety of types of schools participated: public and private schools from both urban and suburban communities. Some offered the program to high-achieving students, while others used CryptoClub as an opportunity to fill a gap in afterschool provisions for students who are usually not eligible for programs targeted for students with special needs. Some offered CryptoClub as a stand-alone program, while others worked it into an existing math club or offered it as an option for students enrolled in an existing school-based afterschool program.

We also had a variety of participants: Students ranged from grade 5 through 8 and there were about the same number of boys as girls. Teachers varied in background; some were math teachers, while others taught all subjects in self-contained classrooms. We also had a social studies teacher, a technology teacher, and a gym teacher.

In each of these pilot years, leaders came to a three-day summer leader-training workshop. We also offered mid-year workshops. These follow-up workshops enabled leaders to network with each other and to give us feedback on what was happening in their programs, however, we found they were not good opportunities to go into depth in content. That is because leaders were at different stages in their implementations and had differing needs for content support.

Students and teachers in the pilot phase worked with an improved set of materials compared to the pre-pilot year. In this phase, we provided versions of the *Cipher Handbook* for each student enrolled in a CryptoClub program. In the beginning of this phase, leaders worked with an abbreviated manual that described games and activities, and by the second pilot year, leaders received a more extensive *Leader Manual* that included lesson guides and extra messages. We were encouraged to observe that with improved material and training, programs covered more content during the pilot phase than during our pre-pilot year.

Data Sources and Analysis
Throughout our pre-pilot and pilot phases, we followed CryptoClub programs as the leaders implemented them at their sites. We gathered data from observations of sessions, focus group interviews with students, and an online survey of leaders.

a) *Observations of CryptoClub Programs*. From 2009 – 2011, we observed 84 sessions across 16 programs from the Chicago area (Table 1). Typically, two CryptoClub researchers visited each program at least twice over the duration of the program. The researchers took field notes during the observations and, often, one of the visits was videotaped. Observations and videotapes, when available, were discussed at weekly meetings of the CryptoClub Project staff. This often resulted in immediate adjustment to our material.

b) *Focus Group Interviews with Students*. We conducted and audio taped seven student focus group interviews with 63 total students, an average of nine students per interview. In these interviews, students had the opportunity to tell us directly their reactions to learning cryptography, whether they thought the materials were engaging, and how they thought the program could be improved.

c) *Online Survey*. Thirteen program leaders completed an online survey about their experiences with CryptoClub, including questions asking them about their overall impressions of the program and ways they felt the program impacted their students. This survey included free-response questions that asked them to describe the best things that happened in their program, their greatest challenges in implementing the program, and what academic knowledge and skills students learned.

Results

What follows are preliminary results, and how they have guided our revisions and further development of our materials.

Learning

The overall impression from all data collected is that students and teachers enjoyed learning cryptography. On the survey, most leaders (10 out of 13) included some of the words "fun," "engaging," "interest," and "enthusiasm" in their answers to open-ended questions about their CryptoClub programs. Similar sentiments are reflected in student responses in focus group interviews. For example, this is a typical response from a student when asked how he or she felt about learning cryptography: "I liked it because it was something new. It was something I hadn't heard about. Yeah, it was really cool – a new experience."

Observers noted that the students appeared to be motivated by the reward they feel after they crack messages. After students have solved something, they often show big grins on their faces and "high five" each other. In one incident in which students were competing to be the first to crack an encrypted quote using frequency analysis, an all-girl team announced they had cracked the quote and were ready to tell the answer. This caused one of the boys to get up quickly and go out into the hall so he wouldn't hear the answer until he had solved it for himself. This desire to personally complete CryptoClub activities was observed in several afterschool programs.

It is difficult to assess the amount of content learning in an informal afterschool setting and therefore we did not pre- and post-test students on math skills. However, in the free-

response survey, student learning and improvement in math were reported by 9 out of 13 teachers. Several mentioned students' use of higher order thinking and problem-solving skills. A teacher wrote:

> It was valuable for students to see over and over that there wasn't one formula to solve each puzzle or crack each code—that they had to employ a variety of strategies and consider the reasonableness of their answers along the way.

Others mentioned improvements in more basic skills, including working with fractions, decimals, and negative numbers. As we observed students engaging in cryptography activities, we noticed teachers taking opportunities to reinforce various mathematics topics. For example, we observed a casual discussion among students about fractions that came up naturally while examining letter frequencies to crack substitution ciphers. The use of fractions and percents in this situation is a meaningful application of those topics and it appeared to interest students.

Teachers reported that students learned not only cryptography and mathematics, but other subjects too. Grammar, vocabulary, and history were areas where they saw cross-curricular benefits. Teachers also reported the program was a good vehicle for learning social studies and improving reading skills.

Ability levels

When asked to name the best thing about the program, one teacher responded that everyone engaged at his or her own level. This made it possible for students from different grade levels to participate in the same program. Some teachers used the program with students who usually perform above average and some with students who perform below average. Teachers also reported that the program gave students who did not usually enjoy or achieve in mathematics the opportunity to enjoy something that is math-related.

Working together

Another theme that emerged was that the CryptoClub encourages students to work together. Eight teachers used the words "relationships," "collaboration," "together," and "teamwork" as they discussed their programs in their survey responses. An observer reported an example of students' cooperative use of reasoning skills as they worked together to crack a message: "I think `J` is `s`." "No! `J` has to be `d` because then it would fit right into `to_ay` and make the word `today`." "Yeah, ok, I think `J` is `d`."

Our observers also noted students teaching each other. This was sometimes needed because sporadic attendance in the afterschool programs often meant that students had missed an earlier topic and had to catch up. One teacher noted that upper grade level students in her program sometimes mentored lower grade level students.

Broader impact

Our observers reported that in several schools, the cryptography theme that began in the afterschool club was used in other school programming. CryptoClub students gave presentations in all-school assemblies and at parent nights. We observed an assembly in

which sixth grade CryptoClub students gave a presentation that included inviting first grade students up to the stage to solve some cryptography problems. A teacher in another program asked her ten CryptoClub students to help teach cryptography to the rest of the class in a month-long special-topic investigation that culminated in an open house with presentations for parents. She commented that her students " enjoyed being experts at something they [might not] have been selected for or assigned to had it been a club based on math performance."

Challenges that guided changes in materials
Our pilot testing revealed some of the challenges in providing a STEM content-based afterschool program. We tried to address these challenges in revisions to our material.

A major challenge is lack of time for leaders to prepare, since most lead afterschool programs in addition to their regular duties. In our early design, we assumed leaders would want to create a lot of their own messages to match their students' interests, so we provided only a few sample messages to go with a core set of games and activities. But our observers noted that leaders did not always have time to create additional material and consequently were not going very deeply into the subject. In their survey responses, several teachers cited lack of time to prepare when asked to name the most challenging things about their program. They asked for more activities that are "ready to go." We realized that even relatively simple tasks such as finding messages and encrypting them before class takes time. We responded by developing more activities and messages, and including them in the next iteration of the *Leader Manual*.

Observers also noted that when leaders did create new material, the content was not always correct or did not always support learning of key ideas. Designing tasks that give appropriate challenges to students at different levels takes both experience with content and understanding of common student errors. This pointed again to the need for us to provide more well-designed activities for teachers to choose from, so we developed and included more in the next iteration of the *Leader Manual*.

Another problem that teachers reported was the need to re-teach material. Some said that because their program only met once a week, students forgot what they had learned in the previous session. Also, because of inconsistent attendance, students might not have been present at the previous session. This motivated the design of the student book in a format ready for quick reference, with an example and short practice all in the same place, so students could quickly locate the main ideas. With this design, our observers have seen students working together to help those that missed a session to catch up.

One teacher reported students completing tasks faster than other students to be a challenge. This is a common problem in most teaching situations and we realized the need to address it in the *Leader Manual*, by pointing out ways lessons can be adjusted to keep all students engaged.

Discussion

There are many challenges in delivering programs that focus on STEM content in afterschool settings. However, the informal environment can offer opportunities to provide students with rich learning experiences that are different from, yet related to, those offered in their regular math and science classes. Our CryptoClub work indicates that it is possible to develop material that meets some of the challenges and takes advantage of opportunities to help students enjoy learning and thinking in their out-of-school time.

Four principles emerged as we developed our cryptography material that we believe may also apply to teaching other interesting and enriching STEM topics in afterschool settings:

1. *Choose a topic that provides a theme that can sustain interest over many sessions*. While exploring an engaging special topic, school-related subjects can come up naturally, allowing students to gain a new perspective on and extend their understanding of the subjects. Investigating a topic over many sessions allows it to be explored in depth.
2. *Activities should be enjoyable, while also making students think*. We found that students enjoyed activities that involved moving around and those that involved competition. While they told us they want "to have fun", we observed that they were not too tired at the end of the day to think and they enjoyed activities that provided those opportunities.
3. *There should be a cohesive set of student materials*. The material should be in a format that makes it easy to teach and re-teach and that enables students to make up missed sessions. In a course of study that builds on and applies earlier concepts, it is important that students have easy reference to these concepts. In our experience, students benefited from having a book that introduced a new topic, provided an example, and provided brief practice, in preparation for other activities that applied the topic.
4. *There should be training for leaders in the specialized content and prepared activities for delivering the content to students*. Professional development, in the form of training and lesson guides can help leaders learn new content and understand its connection to content with which they are familiar. Prepared activities help leaders teach high-quality lessons while cutting down on their preparation time.

We suspect that a fifth principle might emerge from our continued work, but we have not yet evaluated our efforts in this direction:

5. *There should be opportunities for students to extend their learning outside of the program*. These might include problems or activities to take home to share with family and friends. There may be links to relevant Internet sites where students can continue their learning. CryptoClub is developing a website of activities to go along with the afterschool materials, but it is too soon to report findings on its impact.

A final word

In our experience, the opportunity to teach a new and interesting subject in an informal setting brings out creative and enthusiastic teachers. It takes extra work to teach a new subject, yet they choose to do it because they think it will be fun. They bring this attitude to their students in the programs they lead. We believe that afterschool programs built around engaging STEM topics will inevitably attract these special teachers. Ultimately, students will benefit, not only from the content of such programs, but also from the quality of the teachers who choose to lead them.

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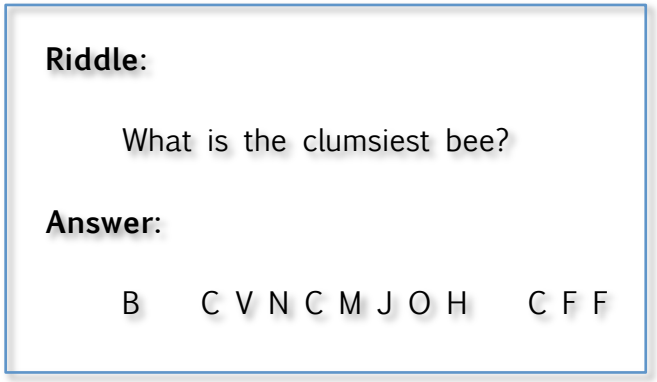

Figure 1: On the first day of CryptoClub, students may be invited to decrypt the answer to this riddle.

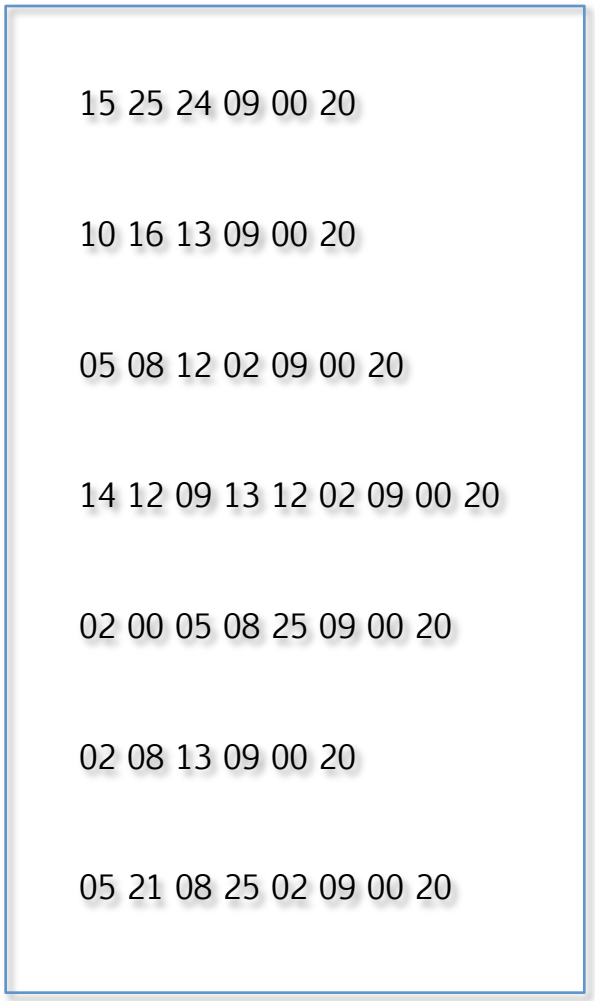

Figure 2: Before formally learning about multiplicative ciphers, students look for patterns to crack this number message.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
00			09	12	15		21	24				10	13	16			25	02	05	08		14		20	

Figure 3: Students make a partial cipher table to help figure out the cipher used in Figure 2.

Table 1

Crypto Club Afterschool Programs 2009-2011			
Type of Program	Urban	Suburban	Total
YPP	4	0	4
Public school	7	3	10
Private school	2	0	2
Total	13	3	16