Research Report

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RESEARCH REPORT

The Development of a Content Assessment of Basic Electronics Knowledge

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This study discusses the development of a basic electronics knowledge (BEK) assessment as a pretest activity for undergraduate students in engineering and related fields. The 28 BEK items represent 12 key concepts, including properties of serial circuits, knowledge of electrical laws (e.g., Kirchhoff's and Ohm's laws), and properties of digital multimeters. This paper first discusses a psychometric evaluation of the BEK assessment to understand its basic measurement properties and to examine various group-level differences based on demographic, institutional, and instructor characteristics. Subsequently, the relationship between BEK scores on the 23 retained items and performance on an existing complex collaborative simulation-based electronics task is discussed. Results demonstrated that basic content knowledge alone may not be sufficient for students to demonstrate knowledge of electronics skills on more complex tasks. The research also carries great importance given ongoing concerns about improving the overall state and diversity of the engineering workforce and its associated pipeline to meet the demands of the national economy.

Keywords collaborative problem solving; educational technology; assessment; electronics; simulation-based assessment

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The engineering component of STEM has garnered more attention recently in K–12 curricula (National Research Council, 2009). The National Assessment of Educational Progress Technology and Engineering Literacy (NAEP TEL) assessment for eighth-grade students covers three primary areas related to in-class and out-of-class experiences: technology and society, design and systems, and information and communication technology—all of which are interrelated. The highlights from the performance results in the 2018 assessment suggested that average NAEP TEL assessment scores for all participants were higher than in 2014. However, when disaggregating by gender, average performance improved only among female examinees. Finally, a higher proportion of examinees reported taking at least one TEL-related course compared to 4 years prior (National Center for Education Statistics, 2018). Thus, it appears that students have recently had more educational opportunities and access to learn about these STEM-related topics associated with the NAEP TEL assessment.

Greater opportunities and access to educational tools aligning with STEM now exist to develop K–12 and postsecondary student interest in the engineering workforce. Students in K–12 have seen an increase in the availability of robotics camps (Williams et al., 2007) and new international competitions incorporating engineering, coding, and teamwork skills (Wisely, 2019). Tran and Nathan (2010), in researching precollege engineering, mentioned one program's success in building a bridge between postsecondary engineering programs and middle schools through integrating engineering concepts into existing curricula (Sanders, 2008).

However, an ongoing concern remains among postsecondary students, namely persistence in STEM majors, especially by women and minorities (Griffith, 2010). Referencing data from the Bureau of Labor Statistics, Sargent (2017) reported that the compound annual growth rate of jobs in the engineering sector through 2026 is expected to be 1.1%, slightly higher than the growth rate for the overall workforce (0.7%). Sargent emphasized the ongoing need to further diversify the engineering workforce. Thus, increased efforts focusing on underrepresented learner populations have become a central focus of researchers and funding agencies alike.

For the higher education community, this important mission requires investment in programming and facilities for helping students and attracting faculty to bolster the pipeline in number and demographic composition. Funding agencies like the National Science Foundation have recently provided financial support to colleges and universities, including

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minority-serving institutions, to develop the STEM student and faculty pipelines (Dobson, 2019; Lehman, 2019; Pine Bluff Commercial, 2019). Corporations have also been investing in university infrastructure (Barr, 2019; Mills, 2019; Ruggles, 2019).

Just as it is important to develop student and faculty pipelines and infrastructure, it is likewise important to focus on STEM-related learning and outcomes for students. Tanner and Allen (2005) found that instructors across content domains and student populations seem to be moving away from just teaching basic facts toward having students gain deeper understanding of key concepts to foster positive learning experiences. There is an additional need to emphasize the structure of engineering learning experiences for students. Marra et al. (2000) showed an enhanced design experience to be positively correlated with intellectual development in one large university's first-year engineering course. The authors suggested that these types of interventions effectively respond to the needs of the engineering workforce and its stakeholders.

This emphasis on structured learning experiences in engineering has also been demonstrated over an extended period with second-year engineering students in Mexico (Polanco et al., 2004) built upon a problem-based learning (PBL) integrated curriculum. The authors found that, relative to a control group, program participants experienced greater pre – post improvement on a baseline test of mechanics knowledge, higher overall grade-point averages, and significantly higher course grades in two of five advanced engineering courses (oral communication and probability and statistics), with higher but nonsignificant grades in three other courses (mechanics, electrical circuits I, and digital systems I). The authors noted that although oral communication is not directly related to engineering, this skill is very relevant to team-based interactions, which are increasingly common in engineering instruction and the profession as a whole (Bagley & Shaffer, 2009).

Measuring Engineering Skills

In order to adequately measure student learning, which can have practical significance on influencing higher education and the corresponding workforce pipeline, particularly in engineering (Sargent Jr., 2017), interpretation of results from pre- and posttest assessments must take into account moderating factors that can influence performance. This is substantiated through a large meta-analysis conducted by Simonsmeier et al. (2018). These authors mentioned that generally, outcomes are possibly moderated by characteristics related to not just knowledge, but the learners themselves, and their environments.

Furthermore, the depth of understanding (Lockhart et al., 1976) may also need to be considered as student performance on certain types of assessments may not necessarily align to student understanding of real-world problems. For example, Norris et al. (2003) discovered that while a large majority of university students studying science had at least a little understanding about five different topics, they still had inherent difficulty interpreting media reports on those topics. O'Reilly et al. (2019) demonstrated with high school students that ecology knowledge beyond a specific threshold can better predict a student's ability to comprehend deeper knowledge on that specific topic. Therefore, in the current paper, we will focus on how depth of electronics knowledge translates into solving complex problems found in engineering.

The Role of Electronics in Engineering

Electronics has a very rich history within the overall engineering industry and is prominently included throughout the standards produced by the leading professional organization in the field, the Institute of Electrical and Electronics Engineers (IEEE). As suggested by Rodriguez-Andina et al. (2010), universities worldwide need to focus on developing interdisciplinary and potential lifelong skills in their engineering students in a faster and more agile way than relying on single-subject courses such as in electronics alone, given how rapidly the technical demands of engineering are changing and the increasing prominence of collaboration and teamwork in the industry. Therefore, it would seem that determining methods to efficiently assess electronics skills in students that could be applied broadly across courses is an important objective.

Means to measuring a fundamental understanding of students' basic electronics knowledge has been explored by Simoni et al. (2004) utilizing concept inventories that were purposefully designed in a multiple-choice format to gage topical mastery as well as identify key misconceptions. They noted a challenge in identifying the most important concepts, as these formed the basis for drafting potential assessment items. The authors drew a distinction between concepts and problem-solving performance such that tasks like performing calculations do not represent a concept but may be necessary in order to solve more complex problems. These researchers cautioned that high conceptual knowledge attainment is necessary, but not sufficient, to attain related mastery of the overall domain.

For example, troubleshooting electrical circuits in a team requires not only electronics content understanding, but also skills such as collaborative problem solving (CPS)[1] which has been deemed important for success across industries in a highly technological 21st century workforce (Burrus et al., 2013). The use of digital tools is the key to assess student performance when presented with challenging and complex real-world problems such as the one just described. These digital tools can record all student actions, including interpersonal chats in some circumstances, allowing for fine-grained analysis of behaviors associated with desired skills. As such, in the current study, students interacted with a complex, simulated environment where multiple students must share knowledge to accurately solve an electronics problem.

Study Purpose

The current paper focuses on analyzing data from a novel BEK assessment to gage student understanding in the electronics content domain. Data were collected from a single testing session involving US undergraduate students in electronics, engineering, and physical science classes. They then worked with a simulation-based electronics assessment designed to measure how students could incorporate their technical BEK knowledge in solving complex real-world electronics problems while showcasing their CPS skills.

A psychometric evaluation of the BEK assessment will be presented first to explain its basic measurement properties and to allow for the examination of various group-level differences based on demographic, institutional, and instructor characteristics. Subsequently, the relationship between BEK scores and performance on the simulation-based electronics task is discussed. Score patterns from the BEK assessment and from the performance assessment will be used to support Simoni et al.'s (2004) assertion, noted previously, that high conceptual knowledge is necessary, but not sufficient, to attain related mastery of the overall domain.

Research Questions

This study examined the following questions:

1. What are the psychometric properties of the BEK assessment and what performance differences exist among key participant subgroups?
2. How does BEK assessment performance relate to performance on a simulation-based electronics task?

Methodology

Participants

The time frame of the study was primarily the Fall 2018 academic semester ($n = 508$), but some preliminary data from two institutions were collected in the Spring 2018 semester ($n = 86$) and from four institutions in the Summer 2018 semester ($n = 44$). Recruitment for the study was conducted using various modalities (e-mail, web page, word of mouth, and face-to-face interactions at conferences). E-mail invitations were sent to over 1,000 electronics education and physics educators familiar to the Center for Occupational Research and Development (CORD) via subsets of mailing lists from the National Career Pathways Network (NCPN), the High Impact Technology Exchange Conference (Hi-TEC), and the National Coalition of Certification Centers (NC3); to postsecondary attendees of the 2018 Summer Meeting of the American Association of Physics Teachers (AAPT) through their e-mail distribution list; and through an October 2018 project presentation run by NCPN.

After completing preliminary agreements, instructors were then invited to register and create classes for testing. A total of 77 instructors responded to the solicitation for pilot testing, 69 were subsequently offered a contract for signature, 49 returned the signed contract, 47 registered to proceed with the study, and 40 were ultimately issued stipends. The initial stipend was $300 USD and then raised to $500 USD to increase participation.

After initial cleaning and validation, the primary sample comprised 599 undergraduate students from 43 classes across 30 US colleges and universities. Basic demographic information on the participating students and the participating institutions is presented on the left side of the tables in Appendix A. Table 1 describes the gender and race/ethnicity of

Table 1 Comparative Gender and Race/Ethnicity Proportions in Study Sample and Undergraduate Engineering Degree Recipients

	Study sample ($n = 599$)		Undergraduate engineering degree recipients in 2016 ($n = 108,976$)[a]	
Student characteristics	*N*	%	*N*	%
Gender				
Female	123	20.5	22,794	20.9
Male	470	78.5	86,182	79.1
Other/prefer not to answer	6	1.0	-	-
Race/ethnicity				
American Indian/Alaskan Native	3	0.5	314	0.3
Asian/Asian American	47	7.8	11,821	10.8
Black/African American	53	8.8	4,206	3.9
Hispanic/Latino	41	6.8	11,337	10.4
Native Hawaiian/other Pacific Islander	4	0.7	160	0.1
White	378	63.1	64,576	59.3
Other/prefer not to answer/unknown	18	3.0	3,122	2.9
Multiracial	55	9.2	3,323	3.0

[a] Data obtained from table 5 – 13 (National Center for Science and Engineering Statistics, 2019).

participating students relative to those receiving undergraduate engineering degrees according to recent data (National Center for Science and Engineering Statistics, 2019).

Collectively, the proportion of non-White students[2] in our sample (33.9%) was slightly higher than that for non-White undergraduate engineering degree recipients overall (28.6%). When comparing specific traditionally underrepresented groups, our sample had a greater representation of Black/African American students (8.8%) compared to undergraduate engineering degree recipients (3.9%); however, our sample had a slightly lower representation of Hispanic/Latino students (6.8%) compared to undergraduate engineering degree recipients (10.4%). The age distribution of participants was such that about 75% were around what might be considered "traditional college age" (i.e., less than 23 years old), with the remainder reporting ages through the highest range of older than 35. This may be indicative of people taking classes as part of additional training or perhaps as part of a new career path.

According to data from the Integrated Postsecondary Education Data System (2017), the 30 participating institutions represented all four geographic regions, consisted of both 2- and 4-year institutions, including eight minority-serving institutions (MSIs), and served a variety of undergraduate population sizes. The participating 4-year institutions represented a range of undergraduate selectivity (Barron's Educational Series, 2017).

The self-reported departmental affiliations of the instructors across the 43 classes primarily included engineering, electronics, and the physical sciences. Some instructors came from what could be characterized as hybrid departments, namely those focusing on engineering and another discipline concurrently. Additionally, although the target population of students was intended to be those in introductory classes, according to their instructors, some classes were considered to be at the intermediate level as well. Among the 41 classes that could clearly be categorized as introductory or intermediate, 27 classes (65.9%, 348 students) were considered introductory and 14 classes (34.1%, 188 students) were considered intermediate.

Instrumentation

Assessment Development Process

The assessment development team consisted of a very diverse group of subject-matter experts including educational and occupational researchers, a community college department head, and a psychometrician. They utilized the in-task assessment framework (I-TAF; Andrews-Todd & Kerr, 2019), which promotes the use of an ontology (Kerr et al., 2016), to graphically depict the conceptual structure of a content domain and the associated relationships therein. The team developed the BEK assessment after evaluating its alignment with the content knowledge needed to complete the existing simulation-based electronics task. This content knowledge includes properties of series circuits, knowledge of electrical laws, and properties of digital multimeters. Such content knowledge is applicable to a range of courses across the electronics, engineering, and physics domains.

BEK Assessment Structure

The resulting BEK assessment consisted of 28 selected response items measuring 12 key concepts represented in the electronics ontology (see Appendix B) across three areas: properties of series circuits (18 items), knowledge of electrical laws (nine items), and properties of digital multimeters (DMMs; eight items). Each of the 12 key concepts was addressed by at least one multiple-choice question and one true–false question, with a few questions addressing more than one of the three primary areas. The BEK assessment therefore measured electronics knowledge, skills, and misconceptions and was not intended to be an inventory of what students knew at that point in their academic careers.

Performance Task

The simulation-based electronics task (see Appendix C) known as the Three-Resistor Activity consisted of four progressively more difficult levels (see Table C1 in Appendix C), requiring progressively more collaboration to achieve success. In the task, students worked in three-person teams, each on a separate computer running a simulation of an electronics circuit. Each team member's circuit board was connected to form a series circuit. Students were tasked with determining the resistance value needed for each circuit's resistor to reach a specified goal voltage value on each board. In later levels, students needed to determine two additional values (i.e., the supply voltage and the resistance for a fourth circuit). Students could use electrical laws such as Ohm's law and Kirchhoff's voltage law to solve the problem and use the interface to communicate, perform calculations, and take measurements to find targeted values.

Instructors randomly assigned three students to a team within their classes. Team members were unaware of other's identities or true levels of domain knowledge, whether on the BEK or otherwise. Therefore, this task not only required electronics knowledge but also CPS skills to effectively solve the problems presented in the task, as students needed to communicate and coordinate their actions to be successful. The system logged chat-based communications reflecting CPS skills and submission of solutions for the required tasks (Andrews-Todd et al., 2018). Task performance was initially measured by both the number of levels a team attempted (range = 1–4) and completed (count of levels A, B, C, and D; range = 0–4). Given not all teams were able to work through the entire activity in the time allotted, the top two levels were consolidated for subsequent analyses.[3] The simulation-based task therefore provided further evidence of student understanding and capabilities represented by a multifaceted system where process data may provide additional validity to claims of students' knowledge and skills (Forsyth et al., 2019) that supplemented the information gathered from the selected response formatted BEK assessment.

Instructor Questionnaires

Instructors also completed preassessment questionnaires regarding the students in their classes concerning, among other topics, their perceived underlying proficiency in electronics. Regarding their students, instructors rated each student's hypothetical levels of electronics skills based on their prior experience with that student, using a 5-point Likert scale (1 = *very weak* to 5 = *very strong*). As a caveat, their confidence in those ratings was also solicited on a 4-point Likert scale (1 = *not at all* to 4 = *very much*).[4]

Analytical Strategy

The first research question regarding the psychometric properties of the BEK assessment and examining subgroup differences was answered initially using traditional dimensionality analyses such as parallel analysis (O'Connor, 2000) and both exploratory and confirmatory factor analyses using SAS 9.4 and LISREL 9.30 (Jöreskog & Sörbom, 2017), respectively. Cronbach's alpha was used to determine internal consistency reliability. SPSS 23 was employed to carry out the t-tests and ANOVAs to examine subgroup differences in BEK scores with the groups defined by information provided by students, institutions, or instructors. The second research question relating students' BEK scores to performance on the simulation-based electronics task was primarily answered through ANOVAs, traditional Pearson correlations, and differences in correlations using the Fisher (1921) method.

Results

Research Question 1

Psychometric Properties of the BEK Assessment

Given that the 28 BEK items were dispersed across the three focal areas, one might hypothesize that the assessment may have been designed to be multidimensional. While a parallel analysis (O'Connor, 2000) did suggest that multiple factors could be present in the data, this model was not championed for formal analyses for two reasons: (a) the development team did not intend for there to be more than just a simple total reported sum score across all items and (b) an exploratory factor analysis to extract more than one factor, using maximum likelihood extraction and promax rotation based on interitem tetrachoric correlations, did not converge.

In subsequently analyzing the psychometric adequacy of the BEK assessment, internal consistency reliability analysis revealed five very poorly discriminating items with item-total correlations below .10, which were removed (final Cronbach's alpha reliability = .80). Across focal areas, two of these (Item 12c, Item 18) covered properties of series circuits, one (Item 10) covered properties of DMMs, and the other two (Item 2, Item 5) covered both properties of series circuits and knowledge of electrical laws. The distribution of these items across key concepts was as follows: Item 2 (5, 7), Item 5 (1, 3, 5, 7), Item 10 (11), Item 12c (4), and Item 18 (6). The removal of these items did not result in the elimination of any of the 12 key concepts. The resulting total score distribution based on 23 items showed no floor effects and minimal ceiling effects ($M = 15.28$; $SD = 4.56$; range = 2–23). Quartiles of the total score distribution were created for further context: Q1 (range = 2–12; $n = 184$), Q2 (range = 13–15; $n = 120$), Q3 (range = 16–19; $n = 165$), and Q4 (range = 20–23; $n = 130$).

Confirmatory factor analyses (Jöreskog & Sörbom, 2017) showed reasonably good fit of the data to a single-factor model (comparative fit index = .93; standardized root mean residual = .09). While these values were slightly below established thresholds, the items generally loaded saliently on the latent BEK dimension (factor loading range = .28–.74; construct reliability = .91).[5] Appendix D provides greater detail on the psychometric information for the 23 retained BEK items.

Examining Subgroup Differences in BEK Scores

Table 2 displays selected performance differences by demographic and institutional subgroups on the BEK assessment. Male and White students respectively outperformed female ($t = 4.98$) and non-White students ($t = 5.16$) in terms of average BEK scores (both $ps < .01$). In both cases, standardized adjusted residuals from chi-square analyses relating BEK performance quartiles to gender and race/ethnicity showed that the higher-performing group tended to have a greater representation of students with BEK scores in the highest performance quartile than expected (male students = 3.2; White students = 3.6) and the lower-performing group tended to have greater representation of students with BEK scores in the lowest performance quartile than expected (female students = 4.6; non-White students = 4.0). No significant differences ($p > .05$) in average BEK scores due to institution type ($t = 1.30$), MSI status ($t = -0.25$), or age (≤ 23 vs. older; $t = -1.59$) were detected. Further analyses related to the possible presence of differential item functioning (Dorans & Kulick, 2006) and distractor functioning (Middleton & Cahalan Laitusis, 2007) were not conducted due to inadequate sample sizes.

Corresponding analyses were conducted to investigate possible mean BEK score differences across instructor department affiliations as well as categorizations of class levels to further gage the appropriateness of the assessment for different

Table 2 Selected Basic Electronics Knowledge (BEK) Score Performance Differences by Demographic and Institutional Characteristics

Demographic and institutional characteristics	Reference group (R)			Focal group (F)			Difference (R-F)	*p*-value	ES
	N	*M*	*SD*	*N*	*M*	*SD*			
Gender: Male (R)/female (F)	470	15.77	4.42	123	13.52	4.66	2.25	<.01	0.50
Race/ethnicity: White (R)/non-White (F)	378	16.01	4.51	209	14.01	4.44	2.00	<.01	0.45
Institution type: 4 year (R)/2-year (F)	344	15.49	4.41	255	15.00	4.74	0.49	.19	0.11
Minority-serving institution (MSI): Non-MSI (R)/MSI (F)	484	15.26	4.47	115	15.38	4.91	−0.13	.80	−0.03
Age: College (R)/older (F)	453	15.11	4.59	146	15.80	4.43	−0.69	.11	−0.15

Note. ES = effect size. Effect size compares reference group mean to focal group mean (Cohen, 1988).

Table 3 Mean Basic Electronics Knowledge (BEK) Scores by Instructor Departmental Affiliation

						Performance quartile (Q) (%)			
Departmental affiliation	*N*	*M*	*SD*	Minimum	Maximum	Q1	Q2	Q3	Q4
Electronics	115	16.41	4.34	2	23	21.7	14.8	34.8	28.7
Engineering	63	15.32	4.25	5	23	23.8	20.6	36.5	19.0
General science	305	14.88	4.73	5	23	35.7	20.7	22.3	21.3
Hybrid	83	15.71	4.33	6	23	27.7	21.7	30.1	20.5
Total	566	15.36	4.57	2	23	30.4	19.6	27.6	22.4

Table 4 Mean Basic Electronics Knowledge (BEK) Scores by Course Level

						Performance quartile (Q) (%)			
Course level	*N*	*M*	*SD*	Minimum	Maximum	Q1	Q2	Q3	Q4
Beginner	348	14.93	4.49	2	23	33.3	21.6	26.1	19.0
Intermediate	188	16.22	4.46	6	23	23.4	17.0	30.9	28.7
Total	536	15.38	4.52	2	23	29.9	20.0	27.8	22.4

learner populations. Table 3 displays the results by instructor departmental affiliation based on cases that the authors felt could be reliably placed into the four categories described earlier (i.e., electronics, engineering, general science, and hybrid; $n = 566$); a small proportion could not. An ANOVA showed an overall mean score difference across the departmental categories (F [3,562] = 3.37, $p = .02$, $\eta_p^2 = .02$). Although the sample primarily consisted of instructors representing general science departments ($n = 305$, 53.9%), mean student BEK performance was lowest for this group ($M = 14.88$; $SD = 4.73$) and significantly so compared to those from electronics departments whose students scored highest on average ($M = 16.41$; $SD = 4.34$; $p = .01$). The ANOVA results showed no significant differences in BEK mean scores between students of instructors representing electronics departments and those representing engineering ($p = .76$) or hybrid departments ($p = 1.00$).

Table 4 shows corresponding information based on those courses categorized as beginner or intermediate ($n = 536$). The mean difference in average BEK scores (1.30) was statistically significant ($p < .01$), with students in intermediate courses having higher BEK scores on average than students in beginner courses ($t = 3.20$).

As mentioned earlier, instructors also provided ratings of their students' proficiency in electronics skills. Of the ratings provided ($n = 442$), the modal category selected was neutral (41.0%) with a comparable proportion of responses categorized as strong or very strong (41.0%). Given this distribution, it was also worth examining average BEK performance by students according to how their instructors assigned their ratings before the students took the BEK assessment. Overall, instructors appeared to generally be reasonably confident in their ratings with 77.1% answering in the top two categories (i.e., 4 = *very much* or 3).

Results displayed in Table 5 show a significant relationship between instructor ratings of students' proficiency in electronic skills and BEK performance through an ANOVA (F [4,437] = 15.73, $p < .01$, $\eta_p^2 = .13$). Specifically, average BEK scores increased as the skill ratings of the students provided by the instructor increased. However, it is worth noting that for those instructors providing ratings in the top two categories ($n = 181$), just over one third of those students (n = 67; 37.0%) had BEK scores that fell within the two lower performance quartiles.

The findings stated in answering Research Question 1 demonstrate that the BEK on its own with this study sample displayed adequate psychometric properties.

Research Question 2

Relationship of BEK Scores to Simulation-Based Electronics Task Performance

Among those with valid log and resulting outcome data from the simulation-based electronics task ($n = 370$; 26 institutions), at the individual student level, an ANOVA showed that mean BEK scores and modal BEK performance quartiles increased with each additional level completed (F [3,366] = 9.56, $p < .01$, $\eta_p^2 = .07$) and attempted (F [3,366] = 8.79,

Table 5 Mean Basic Electronics Knowledge (BEK) Scores by Instructor Perception Ratings of Students' Electronic Skills

						Performance quartile (Q) (%)			
Instructor electronics skills rating	*N*	*M*	*SD*	Minimum	Maximum	Q1	Q2	Q3	Q4
1 (very weak)	15	9.87	3.02	5	15	80.0	20.0	0.0	0.0
2	65	13.06	4.16	6	23	56.9	21.5	10.8	10.8
3	181	15.03	4.47	6	23	32.6	19.3	30.4	17.7
4	108	16.15	4.57	5	23	23.1	20.4	27.8	28.7
5 (very strong)	73	17.44	4.10	8	23	15.1	11.0	37.0	37.0
Total	442	15.24	4.63	5	23	32.6	18.6	26.9	21.9

Table 6 Mean Completed Levels From the Simulation-Based Task by Basic Electronics Knowledge (BEK) Performance Quartile

						Task levels completed (%)			
BEK performance quartile (Q)	*N*	*M*	*SD*	Minimum	Maximum	0	1	2	≥ 3
Q1	117	1.64	1.03	0	3	17.9	23.1	35.9	23.1
Q2	61	1.87	1.09	0	3	16.4	16.4	31.1	36.1
Q3	104	2.02	0.93	0	3	7.7	19.2	36.5	36.5
Q4	88	2.34	0.69	0	3	1.1	9.1	44.3	45.5
Total	370	1.95	0.98	0	3	10.8	17.6	37.3	34.3

Table 7 Mean Attempted Levels From the Simulation-Based Task by Basic Electronics Knowledge (BEK) Performance Quartile

						Task levels attempted (%)		
BEK performance quartile (Q)	*N*	*M*	*SD*	Minimum	Maximum	1	2	≥3
Q1	117	2.39	0.78	0	3	17.9	24.8	57.3
Q2	61	2.48	0.77	0	3	16.4	19.7	63.9
Q3	104	2.60	0.68	0	3	10.6	19.2	70.2
Q4	88	2.86	0.38	0	3	1.1	11.4	87.5
Total	370	2.58	0.69	0	3	11.6	19.2	69.2

$p < .01$, $\eta_p^2 = .07$) performance task level.[6] The respective results are shown in Tables 6 and 7.[7] Even with the complexity and inherent difficulty of the different task levels within the simulation-based electronics task, these results appear to support the notion proposed by Simoni et al. (2004) that high conceptual knowledge is necessary, but not sufficient, to attain related mastery of the overall domain. This is based on the fact that (a) about 10% of those completing one or fewer levels and about 13% of those attempting two or fewer levels of the simulation-based electronics task scored in the highest performance quartile on the BEK assessment and (b) only about half of students in the highest performance quartile completed at least three levels of the simulation-based electronics task.

In general, BEK scores were weakly correlated with the number of task levels completed ($r = .26$; $p < .01$; 95% CI = .16–.37) and the number of task levels attempted ($r = .24$; $p < .01$; 95% CI = .14–.34) on the simulation-based electronics task. We next examined whether these correlations varied by key student demographic groups: gender (male vs. female), race/ethnicity (White vs. non-White), institution type (4-year institutions vs. 2-year institutions), MSI status (non-MSI vs. MSI), and age (college age [≤23] vs. older). There was greater variation in the range of correlations in the focal groups compared to that in the reference groups for both levels completed (focal group range = .20–.49; reference group range = .18–.28) and levels attempted (focal group range = .16–.37; reference group range = .20–.26). The results are displayed in Tables 8 and 9.

Correlations for all reference and focal groups for both levels completed and levels attempted were generally within the 95% confidence intervals for the overall sample, though the correlations for female students on both variables were not significant (*p*s > .05). However, based on the Fisher (1921) method for comparing correlations between BEK scores and simulation-based task levels completed and attempted, only values between BEK scores and levels completed were significantly higher (*p*s < .05) for students attending 2-year institutions and those attending MSIs compared to students

Table 8 Correlations Between BEK Scores and Number of Completed Levels From the Simulation-Based Task

	Reference group (R)				Focal group (F)				Difference
Variable	*N*	Corr.	95% CI	*p*-value	*N*	Corr.	95% CI	*p*-value	Fisher *p*-value
Gender: Male (R)/female (F)	286	.28	.17, .41	<.01	81	.20	−.02, .42	.07	.50
Race/ethnicity: White (R)/non-White (F)	233	.28	.16, .41	<.01	129	.22	.05, .40	.01	.58
Institution type: 4 year (R)/2 year (F)	223	.18	.05, .32	.01	147	.39	.24, .57	<.01	.04
Minority-serving institution (MSI): Non-MSI (R)/MSI (F)	286	.20	.08, .32	<.01	84	.49	.32, .76	<.01	.01
Age: College (R)/older (F)	308	.25	.15, .37	<.01	62	.30	.05, .56	.02	.74

Note. Corr. = correlation; CI = confidence interval.

Table 9 Correlations Between Basic Electronics Knowledge (BEK) Scores and Number of Attempted Levels From the Simulation-Based Task

	Reference group (R)				Focal group (F)				Difference
Variable	*N*	Corr.	95% CI	*p*-value	*N*	Corr.	95% CI	*p*-value	Fisher *p*-value
Gender: Male (R)/female (F)	286	.25	.14, .37	<.01	81	.16	−.06, .38	.16	.44
Race/ethnicity: White (R)/non-White (F)	233	.26	.14, .40	<.01	129	.18	.01, .36	.04	.45
Institution type: 4 year (R)/2 year (F)	223	.23	.10, .37	<.01	147	.25	.09, .42	<.01	.84
Minority-serving institution (MSI): Non-MSI (R)/MSI (F)	286	.20	.08, .32	<.01	84	.37	.17, .61	<.01	.13
Age: College (R)/older (F)	308	.23	.12, .35	<.01	62	.27	.03, .54	.03	.76

Note. Corr. = correlation; CI = confidence interval.

attending 4-year institutions and non-MSIs, respectively. Although the corresponding correlation between BEK scores and number of simulation-based task levels attempted for those attending MSIs was almost twice that for students attending non-MSIs, the resulting difference was not significant ($p = .13$). This indicates greater potential value in relating BEK to solving more complex engineering tasks particularly for students attending 2-year institutions and students attending MSIs.

Conclusions and Future Directions

This paper was written to address whether a newly developed assessment of basic electronics knowledge comprising 12 key concepts in three focal areas displayed adequate psychometric properties for the study sample and across demographic subgroups. After removing poorly functioning items, the remaining 23 items comprising the BEK fit reasonably well to a single-factor latent model with adequate reliability in this sample. Performance differences on average by gender (male students outperformed female students) and race/ethnicity (White students outperformed non-White students) were in line with previous relevant research involving engineering students (Felder et al., 1995; Hackett et al., 1992). That is why encouraging prospective engineering majors in underrepresented groups is important: so they remain interested, confident, and persist to completion of their degrees in the field (Shoemaker et al., 2019). This suggestion is made given the concerns about persistence in STEM majors particularly by female and minority students (Griffith, 2010) and the overall diversity of the engineering workforce (Sargent Jr., 2017).

Although no provision currently exists for reporting subscores from the BEK assessment, diagnostic information is available that instructors of classes across content areas (e.g., electronics vs. general science) and across levels (e.g., beginner vs. intermediate) may find useful. This information is important because students taught by instructors from electronics departments scored higher on average than those from general science departments and students taking intermediate-level classes scored higher on average than those taking beginner-level classes.

Instructors can examine item performance according to the three focal areas or the 12 key concepts, which may suggest material that may need to be reviewed to increase student understanding and reduce possible misconceptions. This could positively affect performance not just on this BEK assessment in the electronics domain, but also across other content domains as well as more complex tasks. We encourage colleagues to take a similarly principled approach to designing instruments such as this.

Information on students' basic electronics content knowledge can still provide a solid foundation of understanding for administering more complex tasks such as the simulation-based electronics performance task described in this paper. This understanding is important because Simkin and Kuechler (2005) discussed how going beyond simply using multiple-choice questions can be helpful to instructors in evaluating student understanding of course content. Therefore, this paper also related BEK scores to performance on a simulation-based task in electronics, known as the Three-Resistor Activity. The results did show that even high basic content knowledge in electronics was not necessarily sufficient for being successful on more complex tasks, consistent with Simoni et al. (2004) in two ways. First, about 10% of those completing one or fewer levels and about 13% of those attempting two or fewer levels of the simulation-based task scored in the highest performance quartile on the BEK assessment. Second, only about half of students in the highest performance quartile completed at least three levels of the simulation-based task.

Moreover, whereas BEK scores and the number of simulation-based task levels completed or attempted were weakly correlated, it should be noted that Norris et al. (2003) also found relationships between knowledge and outcomes that were generally trivial. However, the relationships in this paper across demographic subgroups varied in magnitude, which were important results because as the correlations between BEK scores and simulation-based task levels completed among students attending 2-year institutions and among students attending MSIs approached a moderate level, these were twice those of their 4-year and non-MSI peers, respectively. Therefore, despite low-to-moderate correlations, these results demonstrate the inherent value of measuring BEK, especially for underserved populations.

However, more work is needed to understand factors that may help explain how BEK is leveraged in a group electronics task setting. A substantial proportion of the variance in Three-Resistor Activity performances may be explained by factors such as group dynamics (Steinberg et al., 2018) and how the roles of individual team members relate to accomplishing task goals (e.g. Eaton et al., 2017). This second point is important because correlations between BEK scores and simulation-based task performance were not significant for female students, one of the specific groups Griffith (2010) identified where persistence in STEM majors required attention.

Given inherent mixing of underlying BEK performance scores and perhaps other engineering knowledge among team members when they start the simulation-based task, it suggests the need for developing an individual measure of performance on the task rather than relying on the team-based measures of performance discussed here. Such a transformation could create different dynamics in looking at the relationship between BEK performance scores and simulation-based task performance and potentially better demonstrate the value of the BEK assessment. This may be of particular interest to those concerned about the diversity of the engineering workforce, as for students attending minority-serving institutions, the correlation between BEK scores and levels completed on the performance task was almost twice as a high (.49) compared to the total sample (.26). Additionally, the previous work by Rodriguez-Andina et al. (2010) and Burrus et al. (2013) suggested that collaboration is a skill one must master individually to be successful in workforce settings relevant to engineering.

Furthermore, as an alternative we could have used a performance task that was not collaborative in nature. However, in this project, we already had a complex collaborative electronics task that could readily be used as validity evidence to support the use of the BEK assessment. For future work, we could explore additional tasks that are individual in nature to determine how these might further support the validity argument regarding the use of the BEK assessment.

Additional analyses are planned on the process data from the Three-Resistor Activity (e.g., chat entries, behavioral clicks) to gain a more comprehensive understanding about the collaborative processes during task completion. Some of these discoveries may encourage new explorations which may not only relate to performance on the Three-Resistor Activity, but to where deeper content learning may be required to achieve high performance on such complex tasks. The results from this work should therefore not be used to make recommendations about sufficient electronics preparedness of learners for complex electronics tasks based on BEK skills alone, nor should it be taken to suggest that instructional practices need to be shifted to enhance the teaching of electronics skills.

While the baseline results are encouraging for possible broader implementation, these are based on a pilot with a single, self-selecting yet diverse sample for a single BEK measure and a single simulation-based electronics task. Additionally, future piloting may allow for the development of a more robust scale rooted in item response theory. The analyses presented here did not account for nesting of students within their teams, individual classes, or institutions, but these effects can certainly be explored in future research. Regardless, this study provides some evidence that the BEK assessment designed for this investigation may be a valid measure of students' electronics knowledge.

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Notes

1. Collaborative problem solving is an extremely complex construct beyond the scope of this current paper.
2. Defined as American Indian/Alaskan Native, Asian/Asian American, Black/African American, Hispanic/Latino, Native Hawaiian/other Pacific Islander, and Multiracial.
3. Regardless of whether teams attempted or completed the fourth level, this will be referred to as "≥3," such that it will be understood that all teams attempted or completed at least through the third level. Any direct analyses involving the number of levels attempted or completed utilized 3 as the input value.
4. For hypothetical levels of electronics skill ratings and instructor confidence in those ratings, only the endpoints of the scales were labeled.
5. Thresholds for each statistic are .95 for the comparative fit index (Byrne, 2006), .08 for the standardized root mean residual (Harris et al., 2014), and above .32 for factor loadings (Tabachnick & Fidell, 2014); while there is no clear threshold for construct reliability according to the Hancock and Mueller (2001) approach, it is likely the case the value obtained in this study would be considered more than adequate.
6. Please see the right side of Tables A1 and A2 in Appendix A for demographic and institutional characteristics of this subset of participants. Compared to the total sample, while there were some differences on demographic indicators relative to the full sample, those with valid performance task data scored only slightly higher on average ($M = 15.46$; $SD = 4.66$) than for those without valid performance task data ($M = 15.00$; $SD = 4.38$) but not significantly so ($d = 0.46$; $p = .23$; $ES = 0.10$).
7. Please refer to Footnote 5 earlier with regard to interpreting the "Maximum" column in these tables.

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Appendix A

Summary of Participant Demographic and Institutional Characteristics

Table A1 Demographic Characteristics of Study Participants

	Survey data ($n = 599$)		CPS task data ($n = 370$)	
Student demographic characteristics	*N*	%	*N*	%
Gender				
Female	123	20.5	81	21.9
Male	470	78.5	286	77.3
Other/prefer not to answer	6	1.0	3	0.8
Race/Ethnicity				
American Indian/Alaskan Native	3	0.5	0	0.0
Asian/Asian American	47	7.8	29	7.8
Black/African American	53	8.8	28	7.6
Hispanic/Latino	41	6.8	27	7.3
Native Hawaiian/other Pacific Islander	4	0.7	3	0.8
White	378	63.1	233	63.0
Other/prefer not to answer	18	3.0	11	2.2
Multiracial	55	9.2	39	10.5
Age				
<18	16	2.7	11	3.0
18–20	272	45.4	207	55.9
21–23	165	27.5	90	24.3
24–26	50	8.3	17	4.6
27–29	33	5.5	11	3.0
30–32	26	4.3	15	4.1
33–35	13	2.2	9	2.4
>35	24	4.0	10	2.7

Note. CPS = collaborative problem solving.

Table A2 Institutional Characteristics of Study Participants

	Survey data		CPS task data	
Institutional characteristics	Institutions ($n = 30$), n (%)	Participants ($n = 599$), n (%)	Institutions ($n = 26$), n (%)	Participants ($n = 370$), n (%)
Institution type				
2 year	15 (50.0)	255 (42.6)	11 (42.3)	147 (39.7)
4 year	15 (50.0)	344 (57.4)	15 (57.7)	223 (60.3)
Geographic region				
Northeast	5 (16.7)	87 (14.5)	5 (19.2)	64 (17.3)
Midwest	5 (16.7)	73 (12.2)	4 (15.4)	58 (15.7)
South	17 (56.7)	310 (51.8)	14 (53.8)	192 (51.9)
West	3 (10.0)	129 (21.5)	3 (11.5)	56 (15.1)
Carnegie classification				
Doctoral universities	3 (10.0)	82 (13.7)	3 (11.5)	66 (17.8)
Master's colleges and universities	8 (26.7)	212 (35.4)	8 (30.8)	114 (30.8)
Baccalaureate colleges	4 (13.3)	50 (8.3)	4 (15.4)	43 (11.6)
Associate's colleges	15 (50.0)	255 (42.6)	11 (42.3)	147 (40.8)
Institution size				
Less than 1,000	3 (10.0)	49 (8.2)	3 (11.5)	45 (12.2)
1,000–4,999	6 (20.0)	77 (12.9)	6 (23.1)	57 (15.4)
5,000–9,999	8 (26.7)	100 (16.7)	5 (19.2)	54 (14.6)
10,000–19,999	6 (20.0)	100 (16.7)	5 (19.2)	58 (15.7)
20,000 and above	7 (23.3)	273 (45.6)	7 (26.9)	156 (42.2)

Table A2 Continued

Institutional characteristics	Survey data: Institutions ($n = 30$), n (%)	Survey data: Participants ($n = 599$), n (%)	CPS task data: Institutions ($n = 26$), n (%)	CPS task data: Participants ($n = 370$), n (%)
Minority serving				
Yes	8 (26.7)	115 (19.2)	7 (26.9)	84 (22.7)
No	22 (73.3)	484 (80.8)	19 (73.1)	286 (77.3)
Selectivity				
Most competitive	1 (3.3)	18 (3.0)	1 (3.8)	15 (4.1)
Highly competitive	2 (6.7)	65 (10.9)	2 (7.7)	51 (13.8)
Very competitive	6 (20.0)	108 (18.0)	6 (23.1)	79 (21.4)
Competitive	4 (13.3)	52 (8.7)	4 (15.4)	36 (9.7)
Less competitive	1 (3.3)	18 (3.0)	1 (3.8)	15 (4.1)
Noncompetitive	1 (3.3)	83 (13.9)	1 (3.8)	27 (7.3)
Special/not listed	15 (50.0)	255 (42.6)	11 (42.3)	147 (39.7)

Note. CPS = collaborative problem solving.

Appendix B

Key Concepts Measured in the Basic Electronics Knowledge Assessment

Concept	Focal area	# of items
1. In a series circuit, the current is the same everywhere	A	5
2. In a series circuit, the total resistance of resistors is the sum of the resistor values	A	4
3. In any circuit, the voltage drop across a single resistor is directly proportional to its resistance	B	4
4. In a series circuit, changing one resistance changes the current and voltage drops throughout the circuit	A	3
5. In a series circuit, changing the total circuit resistance changes the circuit current	A	5
6. In a series circuit, changing the circuit current changes all the voltage drops across resistors	A	3
7. In any circuit, Ohm's Law defines a general mathematical relationship between the voltage (E), the current (I), and the resistance (R): $E = I \times R$	B	6
8. In a series circuit, Kirchhoff's law states that the voltage drops across all resistors will equal the voltage supplied	A	6
9. In any circuit, to measure the voltage drop across a single resistor, place the voltmeter probes on opposite ends of the resistor	C	2
10. In any circuit, to measure the total current, break the circuit and place the ammeter probes on the two wires of the break	C	2
11. In any circuit, to measure the voltage supplied by the battery, break the circuit and place the voltmeter probes across the two wires of the break	C	2
12. In any circuit, the digital multimeter will function as a voltmeter (or ammeter) if one adjusts the selector to a voltage (or ammeter) setting	C	2

Note. A = properties of series circuits; B = electrical laws; C = properties of a digital multimeter.

Appendix C

Overview of Three-Resistor Activity

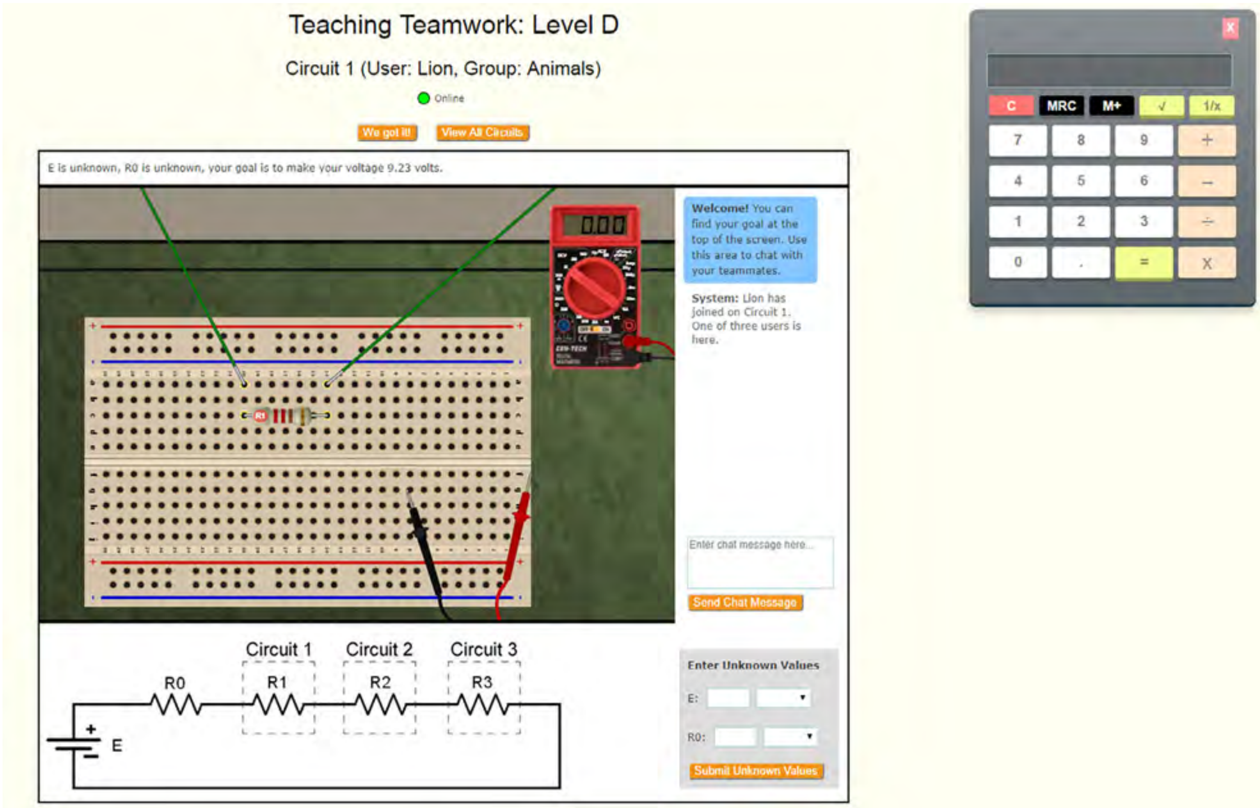

Table C1 Increasing Difficulty of Levels for Teams (Three Students, Three Circuits)

Task level	External voltage (E)	External resistance (R0)	Goal voltages
A	Known by all	Known by all	Same for all
B	Known by all	Known by all	Different for each circuit
C	Unknown	Known by all	Different for each circuit
D	Unknown	Unknown	Different for each circuit

Appendix D

BEK Item-Level Psychometric Information

		% Correct by performance quartile (Q)							
Item	Concepts	Overall	Q1	Q2	Q3	Q4	ITC	Factor Loading	Std. Error
1	5,6,8	.72	.49	.65	.86	.95	.35	.49	.05
3	1,10	.57	.32	.51	.63	.90	.35	.46	.05
4	9	.67	.35	.65	.82	.92	.42	.59	.05
6	1,4,7,8	.65	.41	.58	.73	.93	.33	.44	.05
7	3,8	.43	.16	.26	.49	.89	.47	.69	.05
8	2,7,8	.59	.25	.54	.69	.97	.47	.64	.04
9	1,2,7,8	.59	.34	.46	.68	.95	.38	.54	.05
11	12	.66	.32	.63	.84	.94	.44	.62	.04
12a	2	.93	.83	.94	.99	1.00	.23	.48	.06
12b	3	.48	.26	.44	.50	.82	.30	.40	.05
12d	5	.64	.49	.58	.62	.92	.21	.28	.05
12e	6	.79	.56	.75	.91	.98	.35	.53	.05
13	1	.76	.56	.70	.87	.98	.32	.46	.05
14	2	.92	.79	.93	1.00	1.00	.27	.54	.05
15	3	.59	.38	.53	.63	.90	.26	.36	.05
16	4	.54	.33	.43	.59	.86	.32	.46	.05
17	5	.50	.26	.41	.56	.84	.36	.53	.05
19	7	.92	.83	.90	.96	.99	.19	.42	.07
20	8	.66	.33	.58	.82	.99	.46	.67	.04
21	9	.65	.30	.50	.87	.99	.52	.74	.04
22	10	.62	.28	.58	.79	.93	.42	.59	.05
23	11	.57	.37	.54	.65	.78	.24	.36	.05
24	12	.86	.68	.87	.95	.98	.29	.51	.06

Note. ITC = Item-total correlation; Std. error = standard error.

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