

AN ANALYSIS OF MATHEMATICS REQUIREMENTS AND RECOMMENDATIONS FOR PHD PROGRAMS IN ECONOMICS IN CANADA AND THE UNITED STATES

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Abstract

This paper collects the data on mathematics requirements and recommendations for admission to Ph.D. programs in economics. There are several differences between this paper and Milkman and Marjadi (2017). This paper includes Ph.D. programs in Canada and compares them with the programs in the United States. Then, we split our sample based on whether we had obtained the mathematics course requirements directly from the programs through the questionnaire or phone interview or from the programs' websites. We then analyzed the data to find that there are differences in those requirements and recommendations between programs in Canada and the United States. We also found that there are differences in those requirements and recommendations among different quality tiers.

Keywords: admission requirements; mathematics requirements; Ph.D. in economics

JEL Classification: A230, A20

Introduction

The role of mathematics in the study of economics has long been an issue for debate (Quddus and Rashid 1994; Quddus and Rashid 1990; Hill 1966; Weintraub 2002). We have seen an increasing application of mathematics in modern economics. Consequently, in preparing for new Ph.D.s in economics, many economics Ph.D. programs expect prospective students to possess some mathematical skills. An economics Ph.D. program would normally express this expectation in their admission requirements. It is common or even expected for a Ph.D. program to require or recommend prospective students to have specific mathematics courses on their academic transcripts. One may interpret a "requirement" for a specific mathematics course means that the absence of the course on an applicant's academic transcript will significantly reduce, or eliminate, the probability of admission into the program. On the other hand, one may interpret a "recommendation" for a specific mathematics course means that having the course on an applicant's academic transcript may enhance an application. An economics Ph.D. program may recommend a mathematics course because it believes such course will help students to succeed in their doctoral course of study.

Data

We gathered a dataset on mathematics course requirements and recommendations from economics Ph.D. programs across the United States and Canada. We identified 159 economics

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Ph.D. programs from both Peterson's Guide for Grad School (2015) and the American Economic Association (2015). Then in the Spring and Summer 2016, we surveyed those programs using an online instrument. The survey questionnaire lists eleven mathematics courses commonly mentioned in the admission requirements of economics Ph.D. programs. Those courses are Calculus 1, Calculus 2, Multivariate Calculus, Matrix Theory/Linear Algebra, Differential Equations, Statistics 1, Statistics 2, Econometrics 1, Econometrics 2, Real Analysis, and Stochastic Processes. We asked if any of these courses are required or recommended for admission. We also gave the program directors the opportunity to list additional mathematics courses that were either required or recommended. We emailed non-respondents up to three times and ended up with 75 completed surveys. For the remaining programs, we examined the program's website and we collected 70 completed surveys from the websites of these universities. Some of the programs' websites did not specify prerequisite courses in mathematics, statistics, and econometrics. For those programs we telephoned the program director. All of these efforts resulted in data from 154 Ph.D. economics programs, a collection rate of 96.86%.

Table 1. Mathematic Courses Requirement and Recommendation for Admission to Ph.D. in Economics Programs

Name of University	Tier (2017 ReP Ec)	Calc 1	Calc 2	Mult Calc	Mtrx Lin Algb	Diff Eq	Stoc Proc	Real Ana	Stat 1	Stat 2	Econ 1	Econ 2
American University, US	5	2	2	2	2	1	1	1	1	1	1	1
Arizona State University at the Tempe Campus, US	3	1	1	1	1	1	0	1	1	1	0	0
Auburn University, US ⁾	5	2	2	2	0	0	0	0	0	0	0	0
Binghamton University, US	5	2	2	2	2	2	2	1	2	2	2	1
Boston College, US ⁾	3	1	1	1	1	0	0	1	1	1	0	0
Boston University, US	2	1	1	1	1	0	0	1	1	0	1	0
Brandeis University, US	5	2	2	2	2	1	1	1	2	1	2	1
Brown University, US	2	2	2	2	1	1	1	1	1	1	1	1
Carleton University, Canada	5	2	2	2	2	2	0	0	2	2	2	2
Carnegie Mellon University, US	4	0	0	0	0	0	0	0	0	0	0	0
Claremont Graduate University, US	5	2	2	2	2	0	0	1	2	1	0	0
Clark University, US	5	2	2	2	2	2	0	0	0	0	0	0
Clemson, US	5	2	2	2	2	0	0	1	2	0	2	0
Colorado State University, US ⁾	5	2	2	0	0	0	0	0	0	0	2	0
Columbia University, US	1	2	2	2	2	1	1	1	2	2	2	2
Concordia University, Canada ⁾	5	1	1	1	1	1	1	1	1	1	2	1
Cornell University, US	3	2	2	2	2	1	0	2	2	1	2	1
Dalhousie University, Canada ⁾	5	2	2	0	2	0	0	0	2	2	2	2
Drexel University, US	5	2	2	2	2	1	1	1	2	2	2	1
Duke University, US	3	2	2	2	2	2	1	1	2	1	1	1
Emory University, US	5	1	1	1	1	1	0	1	1	1	1	0
Florida International University, US	5	2	2	1	2	0	0	0	2	1	1	0
Florida State University, US	5	2	2	0	2	0	0	0	2	2	1	0

Name of University	Tier (2017 ReP Ec)	Calc 1	Calc 2	Mult Calc	Mtrx Lin Algb	Diff Eq	Stoc Proc	Real Ana	Stat 1	Stat 2	Econ 1	Econ 2
Fordham University, US	5	2	2	2	2	1	1	1	2	2	1	0
George Mason University, US	5	1	1	0	1	0	0	0	1	1	1	0
George Washington University, US ^{*)}	4	2	2	0	0	0	0	0	0	0	0	0
Georgetown University, US	3	2	2	2	1	1	0	0	2	2	0	0
Georgia Institute of Technology, US	5	2	2	2	2	0	0	0	0	0	0	0
Georgia State University, US ^{*)}	5	2	2	2	1	1	1	1	1	1	1	1
Harvard University, US	1	2	2	0	2	0	0	1	0	0	0	0
Howard University, US	5	0	0	0	0	0	0	0	2	2	2	0
Indiana University Bloomington, US	4	2	2	1	1	1	0	0	1	1	0	0
Indiana University Purdue University Indianapolis (IUPUI), US	5	2	2	2	2	0	0	0	2	2	0	0
Iowa State University, US	4	2	2	2	2	0	0	1	2	2	0	0
John Hopkins University, US	4	2	2	1	2	1	0	1	1	1	0	0
Kansas State University, US	5	2	0	0	0	0	0	0	2	0	0	0
Lehigh University, US	5	2	2	2	2	1	1	1	2	2	2	1
Louisiana State University, US	5	2	2	2	2	1	1	1	2	1	0	0
Massachusetts Institute of Technology, US ^{*)}	1	2	2	2	0	0	0	0	0	0	0	0
McGill University, Canada	5	2	2	2	2	1	1	1	2	2	2	2
McMaster University, Canada ^{*)}	5	0	0	0	0	0	0	0	0	0	2	2
Michigan State University, US	3	2	2	2	2	2	0	2	2	1	0	0
Middle Tennessee State University, US	5	2	1	1	1	0	0	0	1	0	0	0
Mississippi State University, US	5	2	2	0	0	0	0	0	2	0	0	0
New School for Social Research, US	5	0	0	0	0	0	0	0	0	0	0	0
New York University, US	2	2	2	2	2	1	1	2	1	1	2	2
North Carolina State, US	5	2	2	2	2	2	0	1	2	0	1	1
Northeastern University, US	5	2	2	1	1	0	0	1	2	1	0	0
Northern Illinois University, US	5	2	2	1	1	0	0	1	2	2	0	0
Northwestern University, US ^{*)}	2	2	2	2	2	2	0	0	0	0	0	0
Oklahoma State University, US	5	2	2	1	2	1	0	0	2	2	0	0
Oregon State University, US	5	0	2	0	2	0	0	0	2	2	2	0
Penn State University, US	3	2	2	2	0	0	0	0	0	0	0	0
Princeton University, US ^{*)}	5	2	2	2	2	0	0	0	0	0	0	0
Purdue University, US	5	2	2	0	2	0	0	0	2	0	0	0
Rice University, US	5	2	2	2	2	0	0	1	0	0	0	0
Rutgers University, New Brunswick, US	4	2	2	1	2	1	0	1	2	1	1	1
Simon Fraser University, Canada	4	2	2	2	2	1	1	1	2	2	2	2
Southern Illinois University - Carbondale, US	5	2	1	1	1	0	0	0	1	0	1	0

Name of University	Tier (2017 ReP Ec)	Calc 1	Calc 2	Mult Calc	Mtrx Lin Algb	Diff Eq	Stoc Proc	Real Ana	Stat 1	Stat 2	Econ 1	Econ 2
Southern Methodist University, US	5	2	2	2	2	0	0	1	2	0	0	0
Stanford University, US	1	2	2	2	2	0	0	0	2	2	0	0
Stony Brook University, US	5	2	2	1	1	1	1	1	2	2	2	1
Syracuse University, US	5	2	2	2	1	1	0	1	1	1	1	1
Temple University, US	5	2	2	2	2	1	0	1	1	0	1	0
Texas A&M University, US	5	2	2	1	2	1	1	1	2	1	2	1
Texas Tech University, US	5	2	2	2	1	1	0	0	2	2	0	0
The Graduate Center City University of New York, US	5	0	0	0	2	2	0	0	2	0	0	0
The Ohio State University, US	4	2	2	2	2	2	1	1	2	2	1	1
Tulane University, US ⁾	5	2	2	0	0	0	0	0	0	0	0	0
University of California Davis - Economics, US	3	2	2	2	2	1	1	1	1	1	1	0
University of North Carolina Greensboro, US	5	2	1	1	1	1	0	0	2	2	2	2
University of Iowa, US	5	2	2	2	1	1	1	1	2	1	1	1
Universite de Montreal, Canada	5	2	2	2	2	1	1	1	2	2	2	2
Universite du Quebec a Montreal, Canada ⁾	5	0	0	0	0	0	0	0	0	0	0	0
Universite Laval, Canada ⁾	5	2	2	0	2	2	0	0	2	2	2	0
University at Albany, US	5	2	2	2	2	1	1	1	2	1	1	1
University at Buffalo, the State University of New York, US	5	2	2	1	1	1	0	1	1	1	0	0
University of Alabama, US	5	2	2	2	2	2	1	1	1	1	1	1
University of Alberta, Canada	5	2	2	2	2	1	1	1	2	0	2	2
University of Arizona, US	5	2	2	0	2	2	0	2	1	0	1	0
University of Arkansas, US	5	2	2	1	2	1	0	1	0	0	0	0
University of British Columbia, Canada	2	2	2	0	2	2	0	0	2	2	2	0
University of Calgary, Canada ⁾	5	0	0	0	0	0	0	0	0	0	2	2
University of California - Los Angeles (UCLA) , US	3	2	2	0	2	0	0	0	2	0	0	0
University of California - Santa Barbara, US	4	1	1	1	1	0	0	1	1	1	2	0
University of California Irvine, US	3	2	2	2	2	0	0	0	0	0	2	2
University of California, Berkeley, US	1	2	2	2	2	1	2	2	2	2	0	0
University of California, Riverside, US	5	2	2	2	2	0	0	0	2	2	1	0
University of California, San Diego, US	2	2	2	2	2	0	1	1	0	0	0	0
University of California, Santa Cruz, US	4	2	2	0	2	0	0	0	2	2	0	0
University of Chicago, US ⁾	1	2	2	2	2	0	0	0	2	2	2	2
University of Cincinnati, US	5	2	2	2	2	0	1	1	2	2	2	1
University of Colorado, US	4	2	2	1	2	1	0	1	2	1	1	1
University of Connecticut, US	5	2	2	2	2	0	0	0	2	2	0	0
University of Delaware, US	5	2	2	1	1	1	0	1	2	1	2	1

Name of University	Tier (2017 ReP Ec)	Calc 1	Calc 2	Mult Calc	Mtrx Lin Algb	Diff Eq	Stoc Proc	Real Ana	Stat 1	Stat 2	Econ 1	Econ 2
University of Florida, US	5	2	2	2	2	2	0	1	2	0	0	0
University of Georgia, US	5	2	1	1	1	0	0	0	0	0	0	0
University of Guelph, Canada	5	1	1	1	1	0	0	0	2	0	2	1
University of Hawaii at Manoa, US	5	2	2	1	1	1	0	1	0	0	0	0
University of Houston, US	5	2	2	2	1	1	1	1	1	1	1	1
University of Illinois at Chicago, US	5	1	1	1	1	1	0	0	1	0	1	0
University of Illinois at Urbana- Champaign, US	5	0	0	0	0	0	0	1	2	2	0	0
University of Kansas, US	5	2	2	2	2	0	0	0	0	0	0	0
University of Kentucky, US	5	1	1	1	1	0	0	0	1	1	0	0
University of Manitoba, Canada ⁹⁾	5	2	2	0	2	2	0	0	0	0	2	0
University of Maryland at College Park, US	3	2	2	2	2	1	0	2	1	1	1	1
University of Massachusetts - Amherst, US	5	2	2	0	2	0	0	0	2	0	0	0
University of Memphis, US	5	2	1	1	1	0	0	0	2	0	0	0
University of Miami, US	5	2	2	2	2	1	0	1	2	1	1	0
University of Michigan, US	2	2	2	0	2	0	0	0	1	1	0	0
University of Minnesota, Twin Cities Campus, US ⁹⁾	5	2	2	0	0	1	0	1	1	1	0	0
University of Mississippi, US ⁹⁾	5	1	0	0	1	1	0	0	1	1	0	0
University of Missouri, US	5	2	2	1	0	0	0	0	1	0	0	0
University of Missouri-Kansas City, US ⁹⁾	5	1	0	0	1	1	0	0	2	0	0	0
University of Nebraska-Lincoln , US	5	2	2	0	2	1	0	1	2	0	0	0
University of Nevada, Reno, US	5	2	2	0	1	1	0	0	0	0	1	0
University of New Hampshire, US	5	2	1	1	1	1	0	0	2	0	2	0
University of New Mexico, US	5	2	2	0	2	0	1	0	2	1	2	1
University of North Carolina, US	5	2	2	2	2	0	0	1	0	0	0	0
University of Notre Dame, US	4	1	1	1	1	0	0	0	1	1	0	0
University of Oklahoma, US	5	2	2	0	1	0	0	0	2	0	0	0
University of Oregon, US	5	2	2	2	2	1	0	1	2	2	0	0
University of Ottawa, Canada	5	2	2	2	2	0	0	0	2	0	2	2
University of Pennsylvania - The Wharton School, US	5	2	2	2	2	1	1	1	2	1	2	1
University of Pennsylvania, US	2	2	2	2	2	1	1	2	2	1	2	1
University of Pittsburgh, US	4	2	2	0	2	1	0	1	1	1	0	0
University of Rhode Island, US	5	2	2	1	0	0	0	0	2	1	2	1
University of Rochester, US	5	1	1	1	1	0	0	0	1	1	0	0
University of South Carolina, US	5	2	0	0	0	0	0	0	2	2	0	0
University of South Florida, US	5	2	2	0	0	0	0	0	2	0	0	0
University of Southern California, US	3	2	0	0	0	0	0	0	2	2	2	0
University of Tennessee, US	5	2	2	1	2	1	1	1	2	1	2	1

Name of University	Tier (2017 ReP Ec)	Calc 1	Calc 2	Mult Calc	Mtrx Lin Algb	Diff Eq	Stoc Proc	Real Ana	Stat 1	Stat 2	Econ 1	Econ 2
University of Texas, US	4	2	2	2	2	1	0	1	2	2	1	1
University of Texas at Dallas, US	5	2	2	2	2	1	1	1	2	1	1	1
University of Toronto, Canada	3	2	2	1	2	1	1	1	2	2	2	2
University of Utah, US	5	2	1	1	1	1	0	0	2	0	1	0
University of Victoria, Canada	5	1	1	0	1	1	0	0	0	0	1	1
University of Virginia, US	4	2	2	2	2	1	0	1	0	0	0	0
University of Washington, US	4	2	2	1	2	1	0	0	2	2	1	0
University of Waterloo, Canada ^{*)}	5	2	2	0	2	2	0	0	2	2	2	0
University of Western Ontario, Canada	4	2	0	0	2	0	0	0	0	0	0	0
University of Wisconsin - Madison, US	3	2	2	2	2	0	0	0	2	0	0	0
University of Wisconsin - Milwaukee, US	5	2	2	0	0	0	0	0	2	0	0	0
University of Wyoming, US	5	2	2	1	1	1	1	0	1	1	2	1
Utah State University, US	5	2	2	2	1	0	0	0	2	2	2	2
Vanderbilt University, Economics, US	3	2	2	0	1	1	0	1	2	0	1	0
Virginia Tech, US	5	2	2	2	2	1	1	1	2	2	1	1
Washington State University, US	5	2	2	2	2	1	1	1	2	0	2	2
Washington university in St. Louis, US	4	2	2	1	1	1	1	1	1	1	1	1
Wayne State University, US	5	2	2	0	1	1	0	0	2	0	0	0
West Virginia University, US	5	2	1	1	1	1	0	0	2	0	0	0
Western Michigan University, US	5	2	2	0	0	0	0	0	0	0	0	0
Yale University, US	2	1	1	1	1	0	0	0	1	1	0	0
York University, Canada	5	2	1	1	2	1	1	1	1	1	2	2

NOTES:

- Values:
 - 2: Required
 - 1: Recommended
 - 0: Neither required nor recommended
- *) Implicit requirements and/or recommendations

There are several differences between this paper and Milkman and Marjadi (2017). First, this paper includes Ph.D. programs in Canada and compares them with the programs in the United States. Second, when the tier analysis is done we used a different ranking scheme because the ranking scheme used by Milkman and Marjadi (2017) does not contain information about Ph.D. programs in Canada. Third, we split our sample based on whether we had obtained the mathematics course requirements directly from our questionnaire, the phone interview or from a program's Website.

We published a list of the mathematics courses required or recommended for admission to economics Ph.D. programs in the United States (2016) hoping that it may guide aspiring economics Ph.D.s in preparing for their future study. We then published another paper (2017) analyzing the dataset for economics Ph.D. programs in the United States. In this paper, we expand the scope of our analysis to include economics Ph.D. programs in Canada (in the spring of 2019,

there are more than 500 Ph.D. students in Canadian economics programs). Our dataset contains 134 programs in the United States and 20 programs in Canada. Table 1 displays the Mathematics course requirements and recommendations for admission to Ph.D. in Economics programs in Canada and the United States. For each cell in Table 1, there is a number of 2, 1, or 0. The number 2 indicates that the economics Ph.D. department requires that course for admission, the number 1 indicates that the program recommends such course for students, and the number 0 indicates that the course is neither required nor recommended for incoming students. Some of the program directors noted that they also recommend courses in Numerical Methods, Functional Analysis, Probability Theory, Complex Analysis, Topological Space, Convex Analysis, Sets and Logic, Optimization Theory, Game Theory, and Mathematical Economics. If potential Ph.D. students and advisors are using this the information in Table 1, they would want to check whether the requirements and recommendations have changed since the data was collected in 2016.

Analysis of Mathematics Requirements

To illustrate how many mathematics courses that an aspiring economics Ph.D. student may need, we conducted a frequency analysis on our dataset. We counted how many mathematics courses are required for admission by each of the economics Ph.D. program. We also counted how many mathematics courses are required and recommended by each program. We then counted the frequency of programs that require a certain number of mathematic courses. The highest number of mathematics courses required by an economics Ph.D. program is nine. There are two (1.30%) programs that require nine mathematics courses. There are 15 (9.74%) programs that do not require any mathematics courses.

We also counted the number of mathematics courses required or recommended for admission by each of the economics Ph.D. program. There are 29 (18.83%) programs that require or recommend 11 mathematics courses and there are three (1.95%) programs that do not require nor recommend any mathematics courses. Given the almost universal mathematics skill requirements of economics Ph.D. programs, one may wonder the rationale of not requiring or recommending any mathematics courses. One respondent wrote:

“Unlike most graduate programs in economics, we have chosen not to impose rigid course requirements on students. Instead, we emphasize involving students in research early in their graduate careers. Students in the doctoral program ... take courses in order to learn the fundamental principles of economic theory underlying all areas of application, and to master the analytic and modelling techniques of the practicing research economist. In-depth knowledge of specialized areas is required as a by-product of research activity.”

Comparing Mathematics Courses in Canada and the United States

We then compared the frequency of the numbers of “required” and “required or recommended” mathematics courses between the United States and Canada. We arranged the data in contingency tables (Table 2 and Table 3). Then we ran the Fisher’s exact test on each of the tables.

Table 2. Number of Mathematics Courses Required

Country	0	1	2	3	4	5	6	7	8	9	Total
Canada	2	1	4	0	1	1	0	7	3	1	20
% in Canada	10.00	5.00	20.00	0.00	5.00	5.00	0.00	35.00	15.00	5.00	100.00
Cummulative %	10.00	15.00	35.00	35.00	40.00	45.00	45.00	80.00	95.00	100.00	
US	13	5	15	25	22	24	16	10	3	1	134
% in the US	9.70	3.73	11.19	18.66	16.42	17.91	11.94	7.46	2.24	0.75	100.00
Cummulative %	9.70	13.43	24.62	43.28	59.70	77.61	89.55	97.01	99.25	100.00	
Total	15	6	19	25	23	25	16	17	6	2	154
Percent	9.74	3.90	12.34	16.23	14.94	16.23	10.39	11.04	3.90	1.30	100.00
Cummulative %	9.74	13.64	25.98	42.21	57.15	73.38	83.77	94.81	98.71	100.01	

Note: $p < .0001$, Fisher's Exact Test

Table 2 shows that 55% of Ph.D. programs in Canada require seven or more mathematics courses (35% require seven, 15% require eight, and 5% require nine mathematics courses). In the United States, only 10.45% of the Ph.D. programs require seven or more mathematics courses (7.46% require seven, 2.24% require eight, and 0.75% require nine mathematics courses). These results are statistically significant with p -value < 0.0001 . It is clear that the number of mathematics classes required for admission to economics Ph.D. programs is higher in Canada than in the United States.

Table 3. Number of Mathematics Courses Required or Recommended

Country	0	2	3	4	5	6	7	8	9	10	11	Total
Canada	1	3	0	0	1	1	6	0	1	1	6	20
% in Canada	5.00	15.00	0.00	0.00	5.00	5.00	30.00	0.00	5.00	5.00	30.00	100.00
Cummulative %	5.00	20.00	20.00	20.00	25.00	30.00	60.00	60.00	65.00	70.00	100.00	
US	2	4	11	12	13	19	21	11	6	12	23	134
% in the US	1.49	2.99	8.21	8.96	9.70	14.18	15.67	8.21	4.48	8.96	17.16	100.00
Cummulative %	1.49	4.48	12.69	21.65	31.35	45.53	61.20	69.41	73.89	82.85	100.01	
Total	3	7	11	12	14	20	27	11	7	13	29	154
Percent	1.95	4.55	7.14	7.79	9.09	12.99	17.53	7.14	4.55	8.44	18.83	100.00
Cummulative %	1.95	6.50	13.64	21.43	30.52	43.51	61.04	68.18	72.73	81.17	100.00	

Note: $p = .0686$, Fisher's Exact Test

Table 3 combines the required and recommended mathematics classes for admission in both countries. The Fisher's exact test indicate that there is a lower level of statistical significance in the difference between Canada and the United States (p -value = 0.0686).

Table 4. Contingency Table for Calculus 1

	Required	Recommended	Neither Required nor Recommended	Total
Canada	14	3	3	20
United States	115	13	6	134
Total	129	16	9	154

Note: $p = .0841$, Fisher's Exact Test

In order to gain insight into which courses are more frequently required in Canada, we conducted a contingency table analyses, comparing the requirements or recommendations of mathematics courses between Canada and the United States. Table 4 shows an example of a contingency table for Calculus 1. All of the contingency tables for the other courses are listed in the Appendix. We summarize the p -values from Fisher's Exact Test for all the mathematics

courses in Table 5. Table 5 illustrates that economics Ph.D. programs in Canada are more likely to require Statistics 2, Econometrics 1, and Econometrics 2.

Table 5. P-values from Fisher's Exact Test

Courses	<i>p</i> value
Calculus 1	.0841
Calculus 2	.0934
Multivariate Calculus	.1154
Matrix Theory/Linear Algebra	.2978
Differential Equations	.0828
Stochastic Processes	.4446
Real Analysis	.4399
Statistics 1	.2446
Statistics 2	.0325
Econometrics 1	.0001
Econometrics 2	.0001

Quality Tiers

We also attempted to see whether program “quality tiers” make a difference in the mathematics requirements for admission. We defined quality as the level of academic research activity produced by the program. To determine quality tiers, we used a method (Hansen 1991) that puts Ph.D. in Economics programs into five different tiers (“top 6, the next 9, the next 15, the next 18 and the remaining departments”). The tier ranking come from Research Papers in Economics (RePEc, n.d.). It is based on bibliographic data or metadata of over 700,000 publication items of economic research (Zimmermann 2007). The RePEc metadata are continuously updated and the ranking are refreshed monthly. We used the data from August, 2017. RePEc gives a score to each registered author based on several criteria including number of works, citation counts and impact factors. The institution ranking is derived from the aggregate of all authors from that institution. Zimmermann (2007) noted that taking the aggregate scores gives advantage to institutions that have many authors. He added that taking the average scores “...would make little sense, as author registration is not mandatory, and potentially lower ranked authors may be discouraged to register.” We recognized that smaller departments may have a lower ranking, for example Princeton University’s is in tier 5. However, despite its flaws, this is the only ranking of research productivity that includes institutions in the United States and Canada.

We then analyzed the tier ranking to group the programs into the five tiers, constructed the two-way table, and conducted the Chi-square test of independence for each of the courses. We summarize the results on Tables 6 and 7. (Table 1 lists the tier ranking of all of the economics departments in our sample.) It is interesting to note that none of the Ph.D. programs in Canada are in the top tier.

Table 6. Number of Required Mathematics Courses among Different Quality Tiers

Ranking Tier	Number of Mathematics Courses Required										
	0	1	2	3	4	5	6	7	8	9	Total
Frequency											
Row Pct											
1	0	0	0	2	0	0	1	0	3	0	6
	0.00	0.00	0.00	33.33	0.00	0.00	16.67	0.00	50.00	0.00	100.00
2	2	0	0	2	1	1	0	3	0	0	9
	22.22	0.00	0.00	22.22	11.11	11.11	0.00	33.33	0.00	0.00	100.00
3	2	0	0	2	3	3	2	3	0	0	15
	13.33	0.00	0.00	13.33	20.00	20.00	13.33	20.00	0.00	0.00	100.00
4	2	1	4	2	3	2	2	1	1	0	18
	11.11	5.56	22.22	11.11	16.67	11.11	11.11	5.56	5.56	0.00	100.00
5	9	5	15	17	16	19	11	10	2	2	106
	8.49	4.72	14.15	16.04	15.09	17.92	10.38	9.43	1.89	1.89	100.00
Total	15	6	19	25	23	25	16	17	6	2	154
	9.74	3.90	12.34	16.23	14.94	16.23	10.39	11.04	3.90	1.30	100.00

Table 6 shows that two-thirds of the top tier programs requires six or more mathematics courses. This is proportionally more than the other programs in different quality tiers. These differences are statistically significant with p-value of 0.0125. This is similar to the results for the tier analysis in Milkman and Marjadi (2017).

Table 7. Number of Required or Recommended Mathematics Courses among Different Quality Tiers

Ranking Tier	Number of Mathematics Courses Required and Recommended											
	0	2	3	4	5	6	7	8	9	10	11	Total
Frequency												
Row Pct												
1	0	0	1	1	0	1	0	1	1	0	1	6
	0.00	0.00	16.67	16.67	0.00	16.67	0.00	16.67	16.67	0.00	16.67	100.00
2	0	0	0	0	2	2	2	0	0	0	3	9
	0.00	0.00	0.00	0.00	22.22	22.22	22.22	0.00	0.00	0.00	33.33	100.00
3	0	0	1	2	1	1	3	2	0	3	2	15
	0.00	0.00	6.67	13.33	6.67	6.67	20.00	13.33	0.00	20.00	13.33	100.00
4	1	2	0	0	1	2	3	3	0	3	3	18
	5.56	11.11	0.00	0.00	5.56	11.11	16.67	16.67	0.00	16.67	16.67	100.00
5	2	5	9	9	10	14	19	5	6	7	20	106
	1.89	4.72	8.49	8.49	9.43	13.21	17.92	4.72	5.66	6.60	18.87	100.00
Total	3	7	11	12	14	20	27	11	7	13	29	154
	1.95	4.55	7.14	7.79	9.09	12.99	17.53	7.14	4.55	8.44	18.83	100.00

Table 7 also shows that two-thirds of the top tier programs require or recommend six or more mathematics courses.

Implicit v. Explicit Requirements

As noted earlier, after we had closed the survey collection, we attempted to collect the data from the program websites. Many of the programs mention the mathematics course requirements explicitly. Twenty-one programs did not specifically describe their mathematics course requirements or recommendations. However, one can infer the requirements or recommendation from the general admission requirements. We interpreted the requirements from these programs. For example, if the program requires Calculus 2, we can infer that the program requires Calculus 1, even though it is not a listed requirement. Because of this and at a suggestion of a conference discussant, we divided our data into two categories. The first category is where we either have a completed form from the program or have completed a conversation with that program (explicit, n=133) and the second category is where we only have the data from the website (implicit, n=21). Table 1 includes these categories for each program.

Table 8. Number of Required Mathematics Courses, Explicit vs. Implicit

Explicit/ Implicit Frequency	Number of Mathematics Courses Required										
	0	1	2	3	4	5	6	7	8	9	Total
Row Pct											
Explicit	12	4	14	21	22	23	16	13	5	2	132
	9.09	3.03	10.61	15.91	16.67	17.42	12.12	9.85	3.79	1.52	100.00
Implicit	3	2	5	4	1	2	0	4	1	0	22
	13.64	9.09	22.73	18.18	4.55	9.09	0.00	18.18	4.55	0.00	100.00
Total	15	6	19	25	23	25	16	17	6	2	154
	9.74	3.90	12.34	16.23	14.94	16.23	10.39	11.04	3.90	1.30	100.00

Table 9. Number of Required or Recommended Mathematics Courses, Explicit vs. Implicit

Explicit/ Implicit Frequency	Number of Mathematics Courses Required											
	0	2	3	4	5	6	7	8	9	10	11	Total
Row Pct												
Explicit	2	3	8	10	11	19	22	10	7	13	27	132
	1.52	2.27	6.06	7.58	8.33	14.39	16.67	7.58	5.30	9.85	20.45	100.00
Implicit	1	4	3	2	3	1	5	1	0	0	2	22
	4.55	18.18	13.64	9.09	13.64	4.55	22.73	4.55	0.00	0.00	9.09	100.00
Total	3	7	11	12	14	20	27	11	7	13	29	154
	1.95	4.55	7.14	7.79	9.09	12.99	17.53	7.14	4.55	8.44	18.83	100.00

Then, we compared the mathematics course requirements or recommendations between the programs that explicitly mention their requirements or recommendations and those that imply their requirements or recommendations. Tables 8 and 9 are the contingency tables that summarize the number of mathematics courses between the two categories (explicit and implicit). We compared the two categories using Wilcoxon Rank Sum non-parametric test. We ran one test for the number of mathematics courses required and another for the number of mathematics courses required and recommended. For the test on number of mathematics courses required, there is no significant difference between the two categories ($Z=-1.5$, $p=.1232$). However, the other test indicated that economics Ph.D. programs that did not mention specific mathematics requirements or recommendations are likely to have fewer mathematics courses required or recommended, ($Z=-3.2$, $p=.0014$).

Conclusion

This paper reports and analyzes the mathematics requirements and recommendations for economics Ph.D. programs in Canada and the United States. We find that programs in Canada are more likely to require or recommend more mathematics courses than programs in the United States. Our results indicate that programs in Canada are more likely to require Statistics 2, Econometrics 1, and Econometrics 2. We also find that two-thirds of the top-tier programs require six or more mathematics courses. We also find that the explicit programs require more mathematics courses than the implicit programs.

Future research can examine if students who are admitted to Ph.D. programs without the required or recommended mathematics courses have a different completion rate than students who do have the required and recommended courses. While it is true that many economics undergraduate programs are not necessarily focused on training researchers, it may still be the large numbers of mathematics courses that are recommended or required discourage women and minorities from applying to economics Ph.D. programs. Science, technology, engineering, and mathematics (STEM) programs also require many mathematics courses, and they have made significant progress in encouraging more women and minorities to pursue Ph.D.s in the STEM disciplines than those in economics. However, this effort has been backed by extensive funding from both the public and private sector. Also, one might further investigate why programs in Canada require more mathematics courses than programs in the United States.

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Appendix — Contingency Tables for Each Mathematics Course Required or Recommended for Admission.

Calculus 1

	Required	Recommended	Neither Required nor Recommended	Total
Canada	14	3	3	20
US	115	13	6	134
Total	129	16	9	154

Calculus 2

	Required	Recommended	Neither Required nor Recommended	Total
Canada	12	4	4	20
US	105	19	10	134
Total	117	23	14	154

Multivariate Calculus

	Required	Recommended	Neither Required nor Recommended	Total
Canada	6	4	10	20
US	61	38	35	134
Total	67	42	45	154

Matrix Theory/Linear Algebra

	Required	Recommended	Neither Required nor Recommended	Total
Canada	14	3	3	20
US	72	42	20	134
Total	86	45	23	154

Differential Equations

	Required	Recommended	Neither Required nor Recommended	Total
Canada	5	8	7	20
US	11	60	63	134
Total	16	68	70	154

Stochastic Processes

	Required	Recommended	Neither Required nor Recommended	Total
Canada	0	7	13	20
US	2	30	102	134
Total	2	37	115	154

Real Analysis

	Required	Recommended	Neither Required nor Recommended	Total
Canada	0	7	13	20
US	7	61	66	134
Total	7	68	79	154

Statistics 1

	Required	Recommended	Neither Required nor Recommended	Total
Canada	12	2	6	20
US	76	34	24	134
Total	88	36	30	154

Statistics 2

	Required	Recommended	Neither Required nor Recommended	Total
Canada	9	2	9	20
US	32	48	54	134
Total	41	50	63	154

Econometrics 1

	Required	Recommended	Neither Required nor Recommended	Total
Canada	17	1	2	20
US	29	35	70	134
Total	46	36	72	154

Econometrics 2

	Required	Recommended	Neither Required nor Recommended	Total
Canada	11	3	6	20
US	7	33	94	134
Total	18	36	100	154