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■ Research Paper

The Postdoc Queue: A Labour Force in Waiting

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Postdoctoral fellows (postdocs) comprise a large sector of the US scientific workforce. A substantial majority of postdocs are in a holding pattern, seeking tenure-track assistant professorships. We model the postdoc population as a labour force in waiting—in queue. Postdocs enter the queue as they start their first postdoctoral appointment, and they leave in one of two ways: (i) obtaining the ‘queue service’ desired by the majority of postdocs, that is, an assistant professorship, or (2) renegeing from the queue and seeking other positions. Using recent data from the US Survey of Doctorate Recipients, we show that the postdoc queue is one of those rare queueing systems where most of the queuers eventually renege rather than receive service. We find that only about 17% of postdocs ultimately land tenure-track positions. The mean time in queue (postdoc career length) is 2.9 years, with significant variations across disciplines. We discuss policy implications. Copyright © 2018 John Wiley & Sons, Ltd.

Keywords science policy; research policy; science workforce; postdoc; queueing theory

INTRODUCTION

Education and research are both vitally important service sectors of the US economy. To understand and advance our knowledge of these services, it is important for us to know how individuals transition from being doctoral students in research universities to becoming practicing professionals, both within universities and in industry. Today, there is often an intermediate state in the transitioning process, and that is

called *postdoctoral fellow* or *postdoctoral researcher* (postdoc).

Our focus is on new PhD’s in the sciences and engineering and in particular on those who become postdocs after graduation. The majority of postdocs in the sciences and a large fraction in engineering seek to transition from doctoral student to tenure-track assistant professor, in effect emulating the career of their PhD research advisor. Not so long ago, such transitions were done quickly. One of us (the most senior) received the PhD in August and became assistant professor the next month, in September. A second of us, much younger, served 2 years as postdoc, and

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then became tenure-track assistant professor. The most junior of us is now a PhD student, maybe soon to become a postdoc! Most fields have had little or no recent growth in job openings for tenure-track positions (Larson *et al.*, 2014; Ghaffarzadegan *et al.*, 2015; Xue and Larson, 2015). The rate of openings declined in the 1990s, in part due to removal of federal mandatory retirement age, allowing faculty members to remain as long as they want in their tenured positions (Larson and Gomez Diaz, 2012). Over the past few decades, as the production of PhDs has far exceeded the availability of assistant professorships, a new nationally important labour force has grown dramatically—the postdoc labour force, PhDs in waiting.

Various researchers have reported positive impacts of postdoctoral activity on individuals and the tertiary education system (Levey *et al.*, 1988; Gentile, 1989; Teitelbaum, 2008; Su, 2013). Postdoctoral work is seen to be associated with higher productivity, landing high-prestige academic positions and faster securing of first research grants once a faculty member. The resumé building that takes place during postdoctoral work is now almost mandatory for a newly minted PhD who seeks to become competitive in the academic job market. At the institutional level, postdocs help manage research teams, advise students and even offer course lectures, which free up faculty members' time. The postdoc labour force often does what was once exclusively work of faculty members. Some see this use of postdocs as abuse, as a means of growing the university without adding expensive tenure-track faculty slots.

Advocates of postdoctoral positions cite as outcomes improved training and professional development. But others refer to 'holding positions' that new PhDs take mainly due to a shortage in tenure-track opportunities (Hur *et al.*, 2015; Sauermann and Roach, 2016; Kahn and Ginther, 2017). During tough economic times, when fewer tenure-track positions are available, more new PhDs accept postdoc positions (Zumeta, 1984; Zumeta, 1985). In the biomedical sciences, increases in funding are seen to result in longer postdoc durations, larger populations of postdocs and without improved productivity (Hur

et al., 2015). Another factor in US institutions is the high percentage of international PhD students and postdocs. Some may hold different decision-making priorities for their doctoral education and/or willingness to become a postdoc (Hur *et al.*, 2015). Often with lower bargaining power, some of these international emerging scholars may inadvertently be complicit in increasing number of non-tenure-track PhDs in academia.

Today, US institutions host a considerable number of postdoctoral researchers, sometimes even more than the number of tenure-track faculty members. For example, at MIT, the number of tenure-track faculty positions has remained approximately constant at 1000 for 35 years. But the number of postdocs has grown considerably over this period. In MIT, where postdocs were rare only 20 years ago, especially in engineering, each faculty member now has—on average—1.4 postdocs (Massachusetts Institute of Technology, 2015; The Office of Institutional Research, 2015).

Finally, we would be remiss if we did not mention the benefit/cost advantages of hiring postdocs compared with graduate research assistants. In US research universities, the fully loaded cost to a grant or contract of a doctoral research assistant, a student, who works on research 20 to 25 hours per week for 9 months per year, and of course needs tuition waiver, is typically around \$80 per hour. The comparable hourly cost of a postdoc who works about 11 months per year, full time on the grant or contract is typically about \$50 per hour (Sources: MIT, Virginia Tech). One important cost factor is that a research assistant student needs tuition support, and that is provided by the research grant or contract (a postdoc obviously does not pay tuition). As a result, the unit cost of postdocs charged to research grants or contracts is significantly less than that of tuition-requiring graduate research assistants. Moreover, for a postdoc, research productivity is priority one. For a student taking courses, academic success in the courses usually comes first. Finally, the postdoc is a PhD, so knows more about the research domain than a less experienced graduate student. Given the many hours that postdocs

work per week, and considering overhead costs, some have suggested that the take-home pay per hour actually worked is as low as \$18/hour, not much more than the minimum wage in some US cities. The incentives of faculty members to hire postdocs are clear. Some postdocs feel abused by these financial and work-related realities and have formed labour unions, as in the University of California system, with 6500 postdocs in UAW Local 5810 (Camacho and Rhoads, 2015).

Figure 1 depicts the number of postdocs in the United States by major fields from 1987 to 2014. The total number of postdocs grew by 160% from 19,000 in 1987 to 49,000 in 2014. The biomedical sciences field has the largest group of postdocs, while social sciences and psychology are among the smallest (2% of total postdocs).

There is evidence that the primary expectation of postdocs is to land tenure-track positions (Sauermaun and Roach, 2012). A recent study shows that new PhDs who ultimately work in industry but who first choose postdoc training incur a substantial financial penalty (Devin, 2017); it is estimated that postdocs who end up in industry earn about \$240,000 less in their accumulated salary over a period of 15 years (Kahn and Ginther, 2017), in contrast to PhDs who go directly to industry. Tenure-track principal investigators, who hire

postdocs to work in their laboratories, usually counsel them to seek tenure-track positions. Postdocs are generally expected to pursue a career path similar to their supervisors (Reed and Micoli, 2005). Taking the lower paid postdoc position has almost become a necessity for a new PhD to remain and be competitive in the academic job market.

However, the academic job market for tenure-track positions is very competitive, and not everyone can take a permanent tenure-track position. Our past studies show that a small percentage of PhD holders can land such positions (Larson *et al.*, 2014). As depicted in Figure 2, about 46% of all PhD holders from US institutions work in academic institutions. The academic jobs include tenured (21%), tenure-track (7%) and non-tenure-track (18%) positions. The non-tenure-track category includes various positions such as lecturer and postdoc positions. A small portion of PhDs (around 10%) work in the government and a significant portion of them find jobs in businesses or industries. The imbalance between supply and demand of PhD graduates is even worse in engineering and psychology.

Understanding the patterns of inflows and outflows of these young talents to postdoc positions and percentage of success in terms of landing academic positions are important and have major policy implications. In this paper, we develop a simple model to represent the physical system

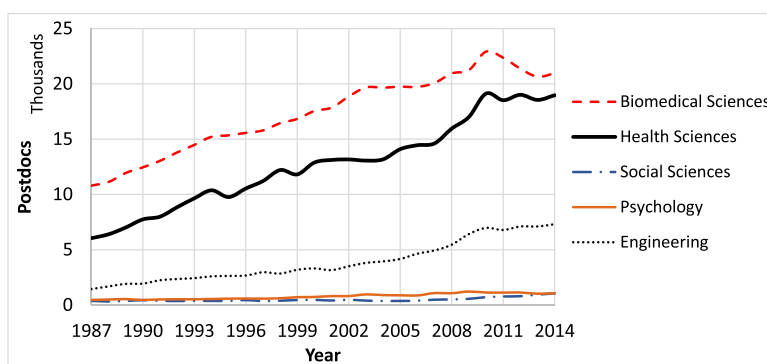


Figure 1 Number of postdocs in the US by major field 1987–2014. Data source: Survey of Doctorate Recipients (National Science Foundation, 2015). [Colour figure can be viewed at wileyonlinelibrary.com]

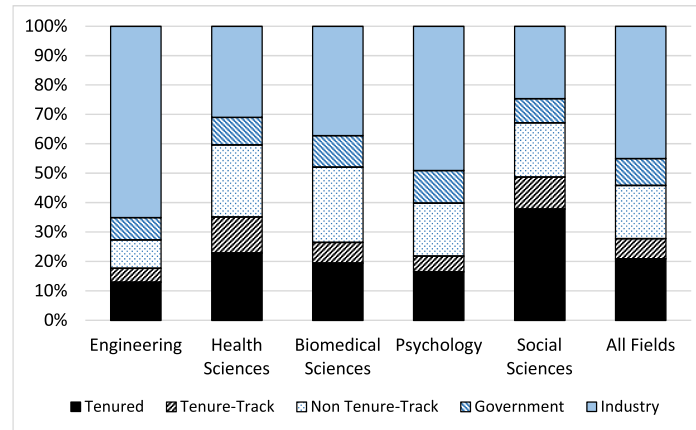


Figure 2 Employer sector of PhD holders from US institutions. Source: authors' estimation from the Survey of Doctorate Recipients 2013 [Colour figure can be viewed at wileyonlinelibrary.com]

and examine the in-flows, out-flows and holding times of the postdoc population, a labour force in waiting. We also speculate on the long-term implications of the growing disparity between young PhDs' faculty career aspirations and market realities.

POSTDOCS IN WAITING

We are not the first to point to the holding nature of postdoc positions (e.g. Zumeta, 1984; Zumeta, 1985). These positions, while relatively low paid, help individuals seek better and permanent positions (Stephan, 2012; Stephan, 2013). In a recent study, Hur *et al.* (2015) empirically investigated people's decision on staying in postdoc positions. They provided evidence for the holding nature of postdoc positions and particularly focused on the effects of change in funding on people's decision to stay in postdoc positions. They showed that more funding results in longer postdoc positions. In simple terms, with more funding people wait longer to find their desired permanent positions (Hur *et al.*, 2015).

Considering the holding nature of postdoc positions, it is important to further investigate system-level characteristics of the holding positions. Specifically, it is helpful to understand how long people are waiting in these positions

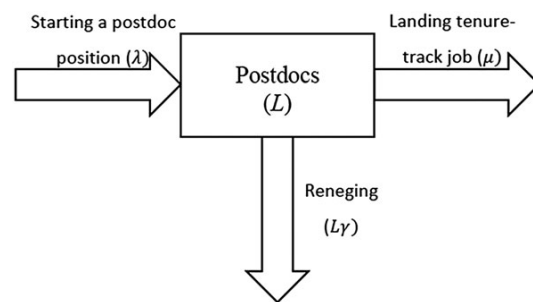


Figure 3 PhD flows in a postdoc queue model

and what happens after waiting in terms of their immediate career choices. A queueing orientation from Operations Research provides an insightful lens through which to analyse 'waiting behaviours'.¹

In this section, we present a simple postdoc queueing model. A postdoc is waiting in a queue, a transitional time to the next step in her or his professional career. As depicted in Figure 3, new PhDs enter the queue with other postdocs and wait until they are either assigned to a server (a tenure-track faculty position) or they leave the queue before being served (reneging).

¹ Here we do consider an individual to remain in the postdoc queue when he or she changes institutes or supervisors but is still employed as a postdoc. According to the dataset, only a small number of postdocs (less than 4%) switched from a non-postdoc position to a postdoc position.

The parameters of this queueing system are as follows:

- *Queue inflow rate (λ)*: The annual arrival rate of new PhDs who take postdoc positions in the postdoc queue.
- *The time-average number of postdocs in the Queue (L)*: This is the average population of postdocs in the queue.
- *Queue service rate (μ)*: The service rate (μ) is the average annual number of tenure-track positions taken by postdocs. ('Service' is the assigning of a queued individual to a tenure-track position.)
- *Reneging rate (γ)*: Individuals who leave postdoc positions to industry or to non-tenure track positions renege from the queue before being served. The parameter γ is the reneging rate per person. Here, $\gamma\Delta t$ is the probability that any given postdoc reneges in the next infinitesimal period of time duration of Δt . Over 1 year, the average number of postdocs who renege from the queue is $L\gamma$.
- *Average waiting time (W)*: This is the mean duration of a postdoc career, equivalent to the mean time spent in the postdoc queue.

We use this framework to study postdocs. Two main questions are as follows: Can we infer the mean waiting time in this queue, given only sampled data about time already spent in queue? What is the net system reneging percentage?

Generally, in most queues, people's willingness to wait is influenced by the time they spend in the queue and the anticipated value of 'service'. For example, if we are holding on a telephone call and we learn that we will have to wait for at least another hour, we will probably hang up, reneging from the queue. For postdocs, the decision may be more complex. One would think that a 'rational' postdoc should weigh and compare the chance of 'being served' with a tenure-track appointment, with its associated value, against the cost of time to wait and the value of alternative career options. But individuals often have little information about costs or chances of landing tenure-track positions, and their decisions may be influenced by their emotions, self-confidence and information asymmetries. A postdoc queue model can help

us all better understand the broader cost consequences of staying in and leaving a postdoc appointment.

Past studies of reneging in different queueing contexts have attempted to model and empirically analyse such a behaviour (Ward and Glynn, 2005), in hospital emergency departments (Batt and Terwiesch, 2015), call centres (Brown *et al.*, 2005), transportation systems (Islam *et al.*, 2014, Wang *et al.*, 2014) and public housing (Kaplan, 1987, Kaplan, 1988). In most of these systems, reneging occurs because the available customer service rate is lower than that required by customers entering the queue. Not everyone can be served. Conservation of flow of 'customers' simply mandates reneging. Else, the reservoir (queue) of customers would grow without bound.

In a study of parking services, Larson and Sasanuma (2010) develop a queueing model of cruising behaviour of drivers while seeking a parking space. In their model, drivers who are cruising the streets to find inexpensive on-street parking are in a moving queue where the reneging behaviour refers to the driver leaving the queue and settling for more expensive off-street parking. Reneging rates can be influenced by different pricing mechanisms for off-street parking, leading to shorter or longer queues of cruising cars.

Our model is similar to the ones developed by Larson and Sasanuma (2010) and Kaplan (1987) in other contexts. We make the following simplifying assumptions.

- 1 We use data from 2008–2013 and assume that the population of postdocs in this time period is relatively steady. Based on Figure 1, the assumption is reasonable.
- 2 We assume that people do not take postdoc positions with the sole intention of becoming more competitive for an industry job. There is no evidence that industries prefer to hire people with postdoctoral training, and as mentioned, there is a huge economic cost associated with doing a postdoc.
- 3 The great majority of postdocs start with a desire for a tenure-track appointment. It is true that at any time, if we look at a current pool of postdocs, not all of them are interested in

tenure-track positions. However, postdoc surveys often have a built-in postdoc-duration bias, as it is not clear at what stage some postdocs start losing their interest in academic positions. Grinstein and Treister (2017) show that interest in academia is much higher at the time of entrance to postdoc positions, potentially above 70%, and then it declines.

- 4 Because the postdoc queue has never been empty in recent times, we also assume that the modelled queue of postdocs is almost always non-empty.
- 5 Finally, the delays and detailed candidate processing associated with hiring a new assistant professor are not modelled here.

Let us return to Figure 3. In each time period, λ people enter the queue and only μ people land tenure-track positions. Given that L is assumed to be in steady state (assumption 1), the fraction of postdocs who become assistant professors is

$$P\{\text{becoming assistant professor}\} = \frac{\mu}{\lambda} \quad (1)$$

Similarly,

$$\begin{aligned} P\{\text{renege}\} &= 1 - P\{\text{becoming assistant professor}\} \\ &= 1 - \frac{\mu}{\lambda} \end{aligned} \quad (2)$$

Furthermore, we can examine the implication of our assumption 1, the steady state condition on outflows: Like a bathtub of water in which the level of water remains constant only if the water inflow is equal to water outflow (the law conservation of mass), the number of postdocs will remain constant if inflow to postdoc positions is equal to total outflow from positions. Thus, in the steady state condition, we have

$$\lambda = \mu + L\gamma \quad (3)$$

And finally, for estimating mean time as postdoc, we can use Little's law of queueing (Little,

1961). Based on this law, the average waiting time in queue is the ratio of mean queue length to inflow rate, as depicted in Equation (4).

$$W = \frac{L}{\lambda} = \frac{\lambda - \mu}{\lambda\gamma} \quad (4)$$

DATA

We next obtain data to provide parameter estimates for the queueing model. We use data from the Survey of Doctoral Recipients (SDR), conducted by the US National Science Foundation (NSF). The NSF survey provides demographic and career history information about PhD holders in science, engineering and health-related fields who received their degree from a US academic institution. SDR follows a sample of individuals throughout their careers. The results of the survey have been used in several past studies to analyse the career development of PhD holders of different demographics that appeared in various journals (e.g. Hur *et al.*, 2015; Hur *et al.*, 2017; Kahn and Ginther, 2017). NSF provides statistical weights to infer population level measures from the sample. NSF anonymized and de-identified the dataset and made it publicly available. More information about the data is available from the NSF Web site.

For the analysis, we use the survey data from 2008, 2010 and 2013, during which period the assumption of a steady-state postdoc queue is reasonable. In this dataset, first we look at the population of postdocs in the fields of biomedical sciences ($n = 1125$), health sciences ($n = 122$), social sciences ($n = 100$), psychology ($n = 206$) and engineering ($n = 412$). We also look at the entire dataset of postdocs ($n = 3652$), which includes all science-related and engineering-related fields. In this dataset, women comprise 44% of the sample, Whites, Asians and underrepresented minorities comprise 47%, 34% and 19% of the sample, respectively.

In addition to individuals' response to their current position, we use two major variables from this survey: (i) graduation date of each respondent and (ii) the time when the survey

was conducted. For each postdoc, the difference between these two variables gives us 'time since graduation' at the time of survey. We use 'time since graduation' for postdocs as an approximation for 'time to date as postdoc'. In simple words, we assume postdoc positions start immediately after graduation (graduation date is the official date of graduation from a PhD programme, and it is often different from the date of commencement ceremony). In reality, some may unofficially start their postdoc positions

before graduation, and some may wait for a while after graduation as unemployed looking for a postdoc position.

RESULTS

Figure 4 shows the distribution of postdoc career durations to date, for five major fields of biomedical sciences (Figure 4a), health sciences (Figure 4b), social sciences (Figure 4c), psychology (Figure 4d),

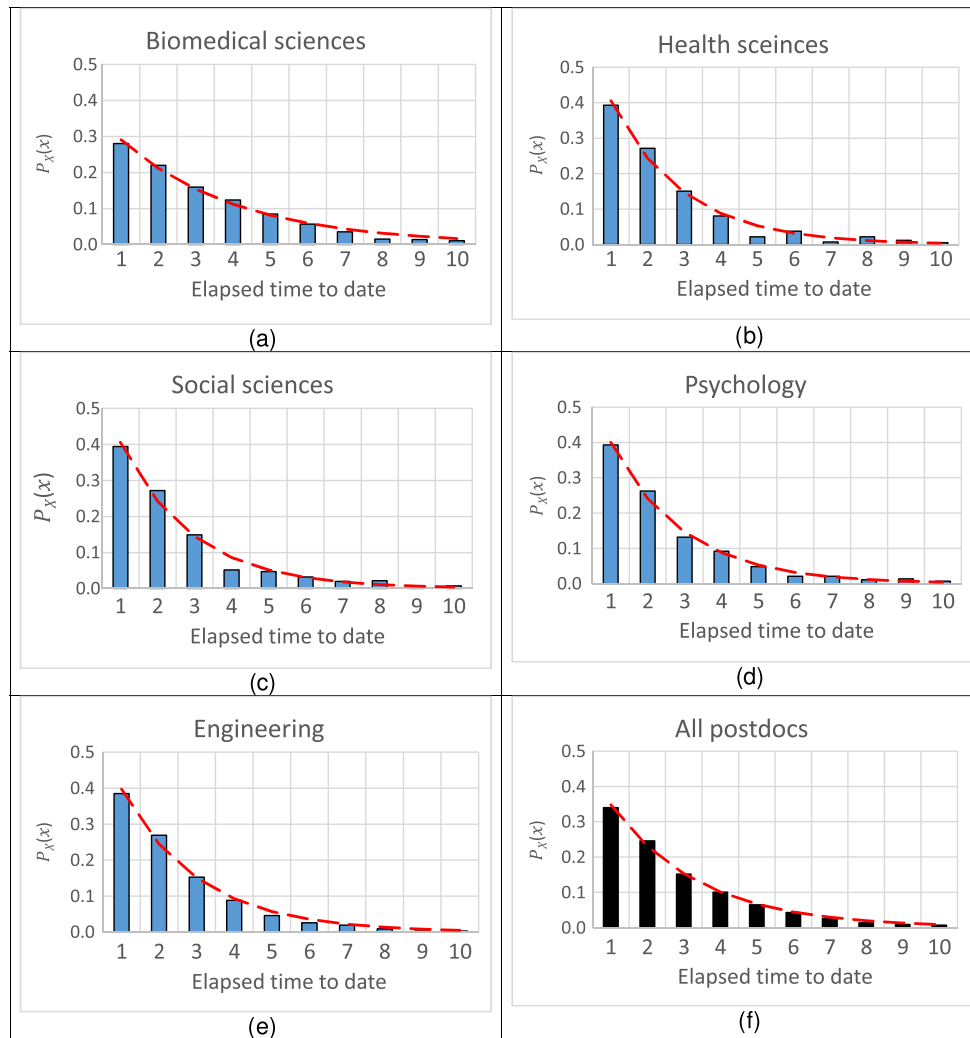


Figure 4 The distribution of postdocs based on years passed since graduation [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 4d) and engineering (Figure 4e), as well as for all fields (Figure 4f). In these figures, $P_x(x)$ is the proportion of postdocs who have been postdocs for at most x years, but for more than $x-1$ years, where integer x must be 1 or greater. The figures also show fitted negative exponential curves that best track the data. The missing data points for the first 1.5 years were estimated by extrapolating backwards the data points from years 2 and 3. We considered individuals with more than 10 years of postdoc as discounted outliers (about 2% of the sample).

In order to use Equations (1)–(4), we first should estimate the annual rate of landing tenure-track jobs (μ) and the annual arrival rate of new PhDs who take postdoc positions (λ). The parameter μ is estimated directly from the data based on the PhD respondents whose current job is a tenure-track faculty position and former job was a postdoc and whose faculty appointment period has been less than 12 months.

The parameter λ is approximately estimated by using the exponential curves from Figure 4. The exponential fitted curves with the general equation of $f(t)$ give an approximation for proportion of postdocs whose ‘time to date as postdoc’ is more than $t-1$ and less than or equal to t , where t can take any number, not necessarily an integer. We used $f(1) * L$ as an approximation for λ .

Next, we use Equations (1)–(4) to estimate probability of renegeing, renegeing rate (γ) and mean waiting time in the queue (W).

Final results are shown in Table 1. As Table 1 shows, about 83% of postdocs will end up renegeing the queue to non-tenure-track positions. These are significantly large fractions and indicate the extent of imbalance between the inflow to the queue and the outflow to the tenure-track positions. In fact, the postdoc queue is one of those rare queues where the majority of people in the queue will not receive the service they had been waiting for.

Reneging rate per person (γ) is also considerable. We find that every year, about 0.28 of all postdocs decide to renege from the queue. This rate is the lowest in biomedical sciences (0.19), while in other fields, the renegeing rate is around 0.28–0.33. Particularly, in engineering,

Table 1 Estimation of properties of the postdoc queues

Fields	$P\{\text{renegeing}\}$	γ	W	Average elapsed time to date
Biomedical sciences	0.69	0.19	3.6	2.6
Health sciences	0.84	0.33	2.5	1.9
Social sciences	0.72	0.28	2.5	2.0
Psychology	0.83	0.33	2.5	2.0
Engineering	0.84	0.33	2.6	1.9
All fields	0.83	0.28	2.9	2.2

psychology, social sciences and health sciences, every year, about one-third of the postdocs decide to leave the queue and pursue non-academic jobs or non-tenure-track positions in academia.

In order to estimate W , mean total time as postdoc, we use Equation (4). Table 1 reports the results. On average, postdoc duration is estimated to be 2.9 years, and across different fields, it seems that biomedical scientists wait for the longest period, 3.6 years. In other fields, the average queue time is around 2.5 or 2.6 years.

It is also interesting to look at the average time-elapsed-to-date for current postdocs. The weighted average of postdoc duration using Figure 4 gives us average elapsed time for the current postdocs. The results are shown in Table 1, right-most column. One intriguing observation is that the average elapsed time spent as postdocs for the current postdoc population is not very different from unconditional average total postdoc duration for newly entering postdocs. For example, the average elapsed time for social sciences and psychology is 2.0 years, while the average total time as postdoc is 2.5 years. One might think that the average elapsed time should be multiplied by a factor of 2 to obtain the average total waiting time. The closeness of the estimations is due in part to the close-to-exponential properties of the distributions. In a perfect continuous negative exponential decline, the elapsed time distribution of the current sampled population of postdocs and total waiting time distribution of newly entering postdocs will be the same due to a ‘random incidence selection bias’ cited by Larson (Larson, 2017). Another curious feature of the negative exponential curve

is that it has the 'no memory' property of Poisson processes. That suggests that a postdoc who has already invested x years as a postdoc ($x > 0$) has the same distribution of additional time as a postdoc as she did when first entering the postdoc queue. Invested time does not appear to reduce the conditional remaining time as postdoc. For more information on how to infer eventual time in a queue from elapsed time-to-date which is usually obtained in cross-sectional surveys, see Larson (2017).

It is worth mentioning that we did not assume that all postdocs, at the time of hiring, are interested in tenure-track positions. Evidence suggests that at least 71% of postdocs and perhaps more wish to become assistant professors at the moment they become postdocs (Grinstein and Treister, 2017). Our analysis shows that only 17% of postdocs land tenure-track positions. So even if we assume that only 70% of postdocs were initially interested in tenure track positions, the chance of landing tenure track positions for ones interested is as low as 24%. This shows the main insight of our model about low chances of landing a tenure-track position after postdoctoral training is robust, and postdoc positions are potentially low return investments for many candidates.

LIMITATIONS OF ANALYSIS

We recognize that our statistical modelling is very aggregate in nature, aiming to obtain first-order insightful results. Delving into the decision making of individual postdocs would, we expect, yield different and quite rich findings on the individual level. For example, a newly minted PhD graduate who is highly interested in getting a tenure-track position in a research university, but whose resume is not yet competitive, may choose to remain a longer-than-usual time as postdoc. Other factors such as field-specific job availabilities attributed to fields lead new PhDs to certain paths, creating different waiting times and renege rates for doctorate holders. In our aggregate analysis, we compare and contrast the field-specific variations of the postdoc queues

but do not attempt to model the decision-making of individuals.

Our primary data source—the NSF Survey of Doctorate Recipients—reports career and personal information of individuals who received their PhDs from US universities. We acknowledge that using SDR data imposes some limitations on the sample population of this study. We lose two groups of doctorate holders: (i) US-trained doctorates who reside outside of the US and (ii) non-US trained doctorates who are postdocs in the USA. Each of these groups may compete with the US-trained postdocs for tenure-track faculty positions. However, excluding them from the sample does not affect the waiting time and renege rate estimates of US-trained postdocs. We are not aware of any major database accurately collecting the information of foreign-trained postdocs. Therefore, losing the aforementioned groups of doctorate holders is inevitable. It is also worthwhile mentioning that since 2015, NSF expanded the sample size of their SDR survey to include US-trained doctorates residing out of the USA. The recent database will provide an opportunity for the researchers to expand our analysis of postdoc queue to both US and non-US careers.

CONCLUSIONS

We applied a queueing model to PhDs who take postdoc positions, with the goal of studying waiting time and renege rates of postdocs. We assume postdocs wait until they get assigned to a server, which is a tenure-track faculty position, or they renege, meaning they leave the queue and accept a non-tenure track position within academia or an industry job. We computed estimates of waiting times in queue and renege rates.

We estimated that 83% of postdocs ultimately renege, or equivalently, only 17% of postdocs eventually land tenure-track positions. Powell (2015) reports that only 15–20% of postdocs in the USA achieve to obtain a tenure-track faculty position, which is confirming our findings. Another study of the postdocs in Belgium reveals that the status of postdocs in landing a tenure-track faculty position is not much different than

the USA. Only 1 out of 10 postdocs in Belgium succeed to find a permanent academic position as a professor (Sven, 2014). Our renegeing rate estimation indicates that in many fields, such as engineering, every year about one-third of postdocs leave the postdoc queue to non-tenure-track positions. Our estimated postdoc career length, that is, in-queue waiting times, for different fields ranges from 2.5 to 3.6 years. The maximum mean waiting time is found in the biomedical sciences.

The study has several implications. First, an average waiting time of 3 years is considerable especially when compared with the average time-to-get-tenure-period of 6 years. Because postdoc assignments are becoming more common, this implies that average age of starting tenure-track positions, average age of getting tenure and, potentially, average age of getting first grant are all increasing. For a typical PhD graduate, it takes about 6 years from high school to finish a Bachelor's and a Master's degree and 4 years (or more) to finish a PhD programme. In simple terms, the waiting time after getting a PhD and before landing a tenure-track position can equal or exceed the time to obtain another degree!

Second, the whole stock of postdocs now competes for tenure-track positions, thereby raising the bar, resulting in more highly qualified individuals taking tenure-track positions. Postdocs have more publications than new graduates and potentially stronger curriculum vitae (Ghaffarzadegan *et al.*, 2014). Later, individuals with more achievements are also more likely to get tenure, leading to lower number of openings due to fewer tenure rejections. This *cycle* exacerbates the academic job shortage for new graduates (Ghaffarzadegan *et al.*, 2016).

Third, at the institutional level, more population of postdocs means a greater supply of inexpensive labour. With their yearning to become assistant professors, and with many not able to accomplish that goal due to mismatch of supply and demand, universities have access to a large captive pool of highly talented individuals who are willing to take low-paid positions to wait until finding their desired permanent positions. In such a skewed labour market, universities have fewer incentives to increase their total numbers

of tenure-track faculty members. This can lead to worsening the situation and potentially longer waiting periods.

Fourth, the majority of the postdocs are funded through federal research grants. As discussed and modelled in other sources (Larson *et al.*, 2012), changes in government research spending can have magnified effects on research institutions and especially on junior researchers, some of whom are employed in postdoc positions. Significant budget cuts will translate to lower job security for postdocs, higher annual rates of renegeing and fewer new postdoc positions.

Overall, our findings and the implications corroborate similar arguments about systemic failure and flaws in academia (Alberts *et al.*, 2014), structural disequilibria (Teitelbaum, 2008) and high faculty reproduction rates, R_0 (Larson *et al.*, 2014). As suggested in our previous study (Ghaffarzadegan *et al.*, 2015), candid data-informed disclosure of the career prospects of potential PhD students is a means to help young scholars make better decisions about their future careers and can assist science policymakers in controlling the current growth of PhD students and postdocs.

We believe that this study also offers a methodological contribution, demonstrating how to use simple physical representations of systems in order to gain insight into social science challenges. Our main physical rule is *the law conservation of mass*: The level of water in a bathtub (number of postdocs) remains constant, if total inflows (the flow of new postdoc appointments) are equal to total outflows (the two divergent flows of tenure-track offerings and renegeing decisions). Another physical rule that we applied, commonly used in operations research, is Little's law of queueing, which gave us an estimate for average time in queue (average duration of being a postdoc). Utilizing such simple physical rules in social systems can provide useful insights.

We should note that the goal of this paper was not to offer precise estimations, but to offer first-order insights into a problem of science workforce development and retention. In this paper, we focused on analysing population-level variables. Future studies can benefit from diving into demographic characteristics and assessing

waiting times for different racial and gender groups and potential associations between these variables and waiting behaviours.

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