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Congressional symmetry: years remaining mirror years served in the U.S. House and Senate

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Abstract

Our overarching goal in this paper was to both test and identify applications for a fundamental theorem of replacement-level populations known as the Stationary Population Identity (SPI), a mathematical model that equates the fraction of a population age *x* and the fraction with *x* years to live. Since true stationarity is virtually non-existent in human populations as well as in populations of non-human species, we used historical data on the memberships in both chambers of the U.S. Congress as populations. We conceived their fixed numbers (e.g., 100 Senators; 435 Representatives) as stationary populations, and their years served and years remaining as the equivalent of life lived and life remaining. Our main result was the affirmation of the mathematical prediction—i.e., the robust symmetry of years served and years remaining in Congress over the approximately 230 years of its existence (1789–2022). A number of applications emerged from this regularity and the distributional patterns therein including (1) new metrics such as Congressional half-life and other quantiles (e.g., 95% turnover); (2) predictability of the distribution of member's years remaining; (3) the extraordinary information content of a single number—the mean number of years served [i.e., derive birth (*b*) and death (*d*) rates; use of *d* as exponential rate parameter for model life tables]; (4) the concept of and metrics associated with period-specific populations (Congress); (5) Congressional life cycle concept with Formation, Growth, Senescence and Extinction Phases; and (6) longitudinal party transition rates for 100% Life Cycle turnover (Democrat/Republican), i.e., each seat from predecessor party-to-incumbent party and from incumbent party-to-successor party. Although our focus is on the use of historical data for Congressional members, we believe that most of the results are general and thus both relevant and applicable to all types of stationary or quasi-stationary populations including to the future world of zero population growth (ZPG).

Keywords: Population stationarity, Stationary population identity, Carey's equality, Brouard's theorem, Congressional life cycles, Period-specific populations, Congressional half-life, Congressional turnover

Introduction

The concept of symmetry would appear to be incongruent with virtually all aspects of a legislative body such as the U.S. Congress with its party divisions, ideological factions, policy schisms and compositional differences in member's regions, ages, gender, ethnicities, politics and religions. However, we discovered a symmetrical regularity over two centuries of historical Congressional data that is consistent with the properties of idealized, mathematically defined stationary populations. Referred to as the stationary population identity (SPI), this model reveals the following: "In a closed, stationary population with fixed birth and death rates the fraction of individuals age x will equal the fraction of individuals with x years to live" (Vaupel, 2009). For example, a hypothetical stationary population with 2% of 85 year-olds will also have exactly 2% of its members with 85 years remaining to live. The paraphrased version of this identity for Congressional data is this: "If entry and exit rates in Congress are both equal and fixed, the distribution of the years served equals the distribution of their years remaining in office." An example in this case would be that if 10% of U.S. Senators have served over 30 years, 10% of the members have 30 or more years remaining.

One reason understanding the relationship of this theory and historical data on years of service for Congressional members is important is that, unlike natural populations that are never stationary, the membership size of the House of Representatives and the U.S. Senate have been fixed at 435 and 100, respectively, since 1959. Therefore, one of the major requirements for population stationarity is met—numerical constancy.

We organized this paper as follows. We first provide background sketches for the stationary population identity, the U.S. Congress, and what we refer to as period-specific populations. We then describe our methods including data sources and concepts for framing our analysis. Next, we discuss our main findings in two parts including one titled Results where we show details with the use of both graphs and tables and another titled Discussion of Results where we interpret and attempt to synthesize the details. We follow these with a two-part section on perspectives and implications of our findings involving both the congressional and the demographic. We close out our paper with a short Conclusion.

Background

Underlying model of symmetry

The mathematical foundations for the theory concerning the mirror images of the distributions for the terms served and left were discovered independently by the French demographer Brouard (1986, 1989) and by the U.S. biodemographer James R. Carey and his colleagues (see Table 1 in Müller et al., 2004, 2007; Carey, 2019; Rao & Carey, 2019a). Whereas Brouard's discovery was contained in two papers he published on stationary populations, both of which were concerned with "years to live" distributions, Carey et al. discovered this relationship and brought it to bear using time-to-death distributions of free-ranging fruit flies to estimate population age structure in the wild. Several years later demographer Vaupel assigned the eponym Carey's Equality to this mathematical identity and published a formal proof (Vaupel, 2009) to complement the one in Brouard's earlier papers. Both demographers presented mathematical proofs that in a closed, stationary population the probability an individual who has lived x years, denoted $c(x)$, equals the probability an individual has that same number of years left to live, denoted $g(x)$. That is

$$c(x) = g(x). \quad (1)$$

Note that the age-weighted integrals of each side over all ages shown here

$$\int_0^{\omega} xc(x)\mathrm{d}x = \int_0^{\omega} xg(x)\mathrm{d}x \tag{2}$$

gives the equality of the mean age of the population (left integral, denoted $\bar{c}$) and the mean number of years remaining for the average individual (right integral, denoted $\bar{g}$):

$$\bar{c} = \bar{g}. \tag{3}$$

This same relationship between means was published in separate papers by Kim and Aron (1989) and Goldstein (2009), the latter author of whom noted that increases in $\bar{c}$ can be seen as making the population "older"; but increasing distance from death $\bar{g}$ can be seen as making the population effectively younger. Sanderson and Scherbov (2005) illustrated the concept that populations (and Congress by extension) can at once become both older and younger when $\bar{c}$ and $\bar{g}$ both increase, the former corresponding to increases in average population age and the latter corresponding to decreases in relative age due to increases in time-to-death.

Applications of the equality include estimates of $\bar{g}$ when $\bar{c}$ is more easily observed—undoubtedly the most common situation. Vaupel (2009) noted that more than 48% of hypothetical individuals are 41 years old or older in the 2005 U.S. lifetable. This implies that nearly half of the life table population will be alive in 2050, a date 41 years from the time he published his 2009 paper, a year that at the time was considered as being in the distant future. Kim and Aron (1989) illustrated the practical application by noting that the average *remaining* time in households could be inferred from the average time in the household.

However, there are cases when $\bar{g}$ is more easily observed as was the situation for estimating population age structure in the wild due to the virtual impossibility of monitoring the lifespan of free-ranging fruit fly adults. In this case the post-capture (i.e., remaining) lifespans of flies removed from the wild and monitored in the laboratory were used (with adjustments from reference life tables) to estimate age structure (Carey, 2011; Carey et al., 2008, 2012; Müller et al., 2004).

U.S. Congress: a synopsis

The United States Congress is the federal, bicameral legislature of the United States, and was founded on March 4, 1789 by Article One of the United States Constitution. The Connecticut Compromise Plan established the bicameral structure of the Congress, wherein the lower House, the House of Representatives, would have membership proportioned by population, and the upper house, the Senate, would have two representatives allotted to each state. Since the beginning, the size and calculation of apportionment has remained a controversial political issue. Until 1910 (when the chamber was expanded from 391 seats to its eventual 435), the House had experienced patterns of growth—the number of seats in the House did not increase only after the 1840 census. With one exception, the House has been capped at 435 members since 1912. The maximum population of the Senate has thusly changed as each new State added to the country, starting at 22. This number increased to 24 in 1789 with the addition of the first new state (North Carolina) and eventually capped at 100 in 1959 when the 49th and 50th states were added (Alaska and Hawaii).

Congress as population

As Preston and his co-authors note (Preston et al., 2001, p. 57), any collection of individuals meeting some defined criteria for membership has a set of attrition or death rates (denoted *d*) that describe the process of leaving the population as well as a concomitant set of birth rates (denoted *b*) that describe the process of entering. Analysis of data on congressional member's service is important because: (1) Congressional careers represent life courses with age class (time-in-service) equivalents that last up to 50 years; (2) the population is closed to migration, has fixed numbers and thus is numerically stationary; (3) Congressional members have multiple exit pathways including election loss, retirement; expulsion or death, all of which could be used to conduct "cause elimination" studies using life table methods; (4) Congressional members are diverse with respect to gender, ethnicity and state, and (5) databases are extraordinarily comprehensive (230 years), complete (100% of all members) and accurate (exact dates of entry and exit).

Methods

Data source

The names and years of service for all persons who ever served in the U.S. Congress starting in 1789 and ending in 2022 were downloaded from the website GovTrack (2022). These data contained information for the over 12,000 individuals who served as Representatives, Senators, or in both capacities since the U.S. Congress convened on March 4, 1789 (HouseGov, 2022). Depending on historical period approximately 5 to 10% and 3 to 5% of House members and Senate members, respectively, served discontinuous periods in congress (i.e., out-of-office periods between congressional membership periods).

We used only the first service period of these multi-period congressional members in our analysis and graphics for two main reasons. First, all alternatives to data censoring introduce their own set of conceptual and/or analytical biases. For example, most of the subsequent congressional periods served after the first by multi-period members were substantially shorter than those served by congressional members overall. Therefore, treating the congressional periods served after the first as separate "career-courses" would suggest a greater frequency of shorter congressional membership periods than were actually observed. Second, the overriding objective of our study was proof-of-concept and censuring the relatively modest amount of data that fell into this category was simple, straightforward and transparent. Therefore, the censuring maintained the focus of our study on the robustness of the results rather than on the nuances, fine details and/or explanations that would have been required had we attempted to fit and/or re-purpose these data to the model in other ways.

Years served and remaining

We created two sets of distributions involving the members of both the House and the Senate for each of the 180 years from 1800 through 1980—the distribution of years served and the distribution of years remaining. From these distributional data we then: (1) compared the average number of years served ($\bar{c}$) with the years remaining

($\overline{g}$); (2) visualized graphically the symmetry of the two distributions; and (3) calculated the correlation coefficients for use as statistical proxies for comparing the extent to which the distributions were symmetrical.

Visualization

The average member of a population of fixed size and subject to constant birth and death rates will have lived half of their life (life-lived) and thus have half of their life remaining (life-left).

Member lanes (Fig. 1a)

Consider the US Senate as a population with each member occupying a single seat and with the population collectively depicted as a series of horizontal lanes moving from left to right through time. Just as the membership of the U.S. Senate is fixed at 100, the number of lanes is also fixed at this number. This "iron rule" of congressional membership mandates that one member must exit a seat before a new member can occupy it—i.e., every year the number of births must exactly equal the number of deaths.

Staggered years of membership (Fig. 1b)

Properties of the Senate members that are subject to on-going replacement by birth and death (election/retirement/attrition) processes include both the number of years served and the number of years remaining, a visualization for 100 hypothetical members of the Senate of which is presented in Fig. 1b at time $t = 50$ years. Note the wide range of values for each of the two segments on each side of the 50-year midpoint ranging from members who have served only a few years but have many years remaining to members who have served many years and have only a few years remaining.

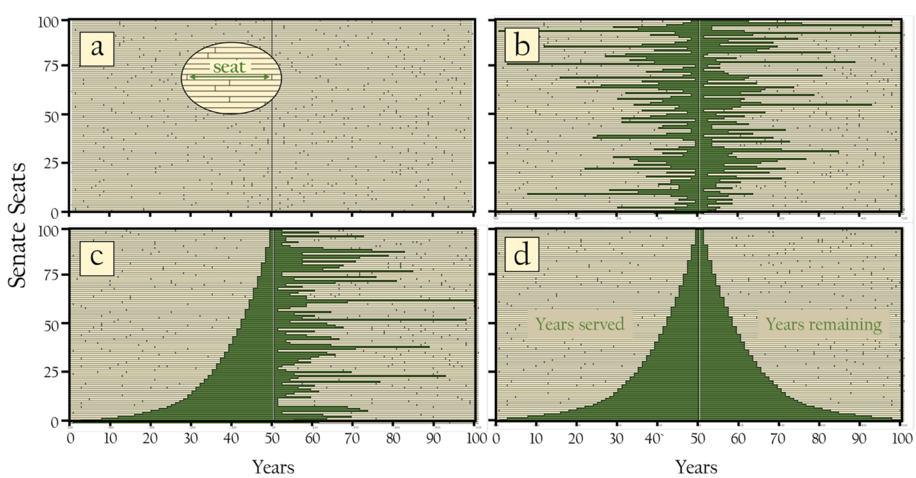

Fig. 1 Depiction of horizontal lifelines for a hypothetical 100-member Senate for one century. Each horizontal line represents a seat with interspersed green ticks depicting a change-of-seat. The solid green lines depict the years served by individual members who were jointly serving in year 50 (i.e., current hypothetical year). **a** Hypothetical 100-seat "lanes" with inset showing in-office duration of one member for approximately 20 years; **b** random vertical distribution of lifelines for current members; **c** lifelines of current members ordered shortest-to-longest from top-to-bottom according to years already served; **d** lifeline segments of current members for years served and years remaining decoupled and each ordered shortest-to-longest from top-to-bottom. Note the mirror-image symmetry of the two distributions

Rank-ordered years served (Fig. 1c)

Ordering membership “lanes” from top (shortest) to bottom (longest) according to the years served reveals the exponential distribution of this membership traits as depicted in Fig. 1c. The right-hand side of this visual contains the staggered distribution of years remaining as an outcome of the unequal distribution years served in the senate by its members. However, note that none of the very longest-serving members have extreme numbers of years remaining. Virtually all of the members with many years remaining are the junior.

Symmetrical distributions (Fig. 1d)

The final step in this rearrangement involves decoupling the years served and years remaining for each member and ordering the terminal segments (right-hand side) from top (shortest) to bottom (longest) according to years remaining. This step reveals the symmetry and thus the equality of the two distributions in this idealized case—i.e., years served equals years remaining.

Congressional life cycle (CLC) model

Inasmuch as the life table identity model considers years served and years remaining in the Congressional population for each of its individual members, we use this concept to create a Congressional Life Cycle (CLC) model (Fig. 2). We consider a CLC as having formed retrospectively the year the oldest member was elected, and ending at extinction

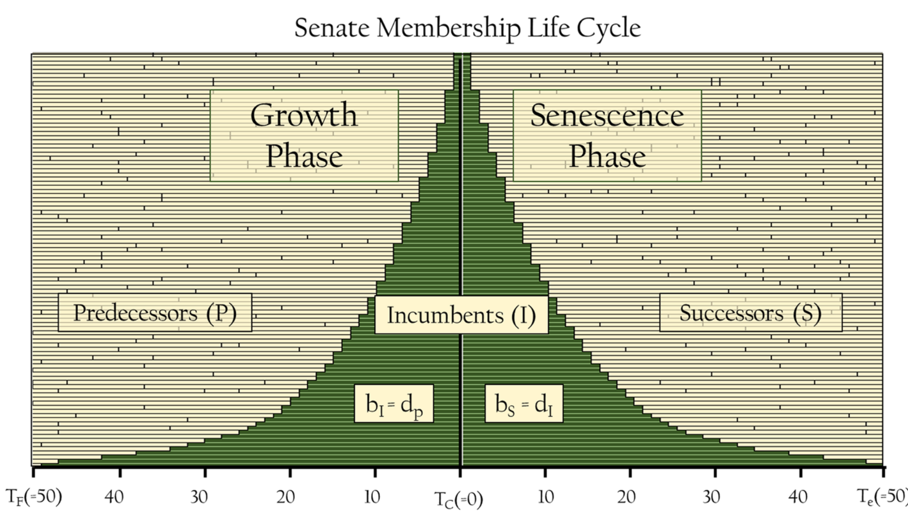

Fig. 2 Stationary Population Identity (SPI) model (see Fig. 1) conceived as a Congressional Life Cycle (CLC) model. The green-shaded area indicates the distribution of years served (left) and years remaining (right) by the population at the midpoint with the terms of the predecessors they replaced immediately to the left and the successors who replaced them immediately to the right. Formation begins retrospectively at the election of the most senior member, time T_F 50 years earlier, membership grows incrementally for the next 50 years through completion at time T_C and then senesces for the following 50 years to extinction at time T_E when the last member leaves office. Note that the birth rate of the incumbents (b_I) equal the death rates of their predecessors (d_P) in the Growth Phase, and that the death rate of the incumbents (d_I) equals the birth rate of their successors (b_S) in the Senescence Phase. Also note that each “step” (new election) in the Growth and Senescence phases represents the transition of a Senate seat FROM one party TO either the same party or the opposing one. There are thus 100 party transitions in each phase spanning 40 or more years and 200 total party transitions across the entire CLC spanning 80 or more years

when the last member exits. Between these two bounding events, the population first grows by adding new members and senesces by subtracting the incumbent members.

In the growth phase we define the population's doubling time (DT), as the time required for the population to increase by twofold starting at formation, the formula of which is given as

$$\mathrm{DT} = \frac{\ln(2)}{b}. \tag{4}$$

As an example, if $\bar{c} = 7$ then its inverse is $b = 0.14$ and $\mathrm{DT} = 5$. Thus starting at one individual the population will increase by 2-, 4-, 8-, and 16-fold in 5, 10, 15, and 20 years, respectively.

The population's half-life (HL) the time required for the fully formed population to decrease by half is similarly computed but, in this case, using ln(0.5) in the numerator and death rate, *d*, in the denominator. This formula is given as

$$\mathrm{HL} = \frac{\ln(0.5)}{d}. \tag{5}$$

As an example, if $\bar{g} = 7$ then its inverse is $d = 0.14$ and $\mathrm{HT} = 5$. Thus the population will decrease by a half, a quarter, an eighth and a sixteenth in 5, 10, 15 and 20 years, respectively.

The values for both DT and HL also indicate the number of years of overlap for each of the respective fractions of the population. For example, career overlap occurs for 5, 10 and 15 years in one-half, one-quarter and one-eighth of the members for both their years served and their years remaining in the hypothetical population described above.

Results

Years served and remaining

Means

Plots of the average number of years served and the average number of years remaining for both House and Senate members throughout the nineteenth and twentieth centuries and the first two decades of the twenty-first century are presented in Fig. 3a, b. Two aspects of these graphs merit comment. *First*, the averages trended upward starting at around 4 to 5 years in the early nineteenth century to 10 or more in the late twentieth. Average number of years served exceeded 15 years in the first two decades of the twenty-first century. *Second*, the average number of years remaining exceeded the years served because of (a) new states and thus additional Congress members added; (b) increasing propensities for members wishing to stay in office; and (c) increasing rates of re-election.

Distributions

The average number of years served and left in the Senate for 1830, 1900, 1950 and 1980 are 5.9 vs. 5.2, 8.3 vs. 8.2, 8.2 vs. 11.2 and 10.7 vs. 13.6 years, respectively (Fig. 4a, b). The average number of years served vs. years left in the House for this same set of years are 3.6 vs. 3.2, 4.5 vs. 6.3, 8.4 vs. 9.4, and 9.4 vs. 9.4 years, respectively. Although the mean number of years served and mean number of years remaining differed by 10 to

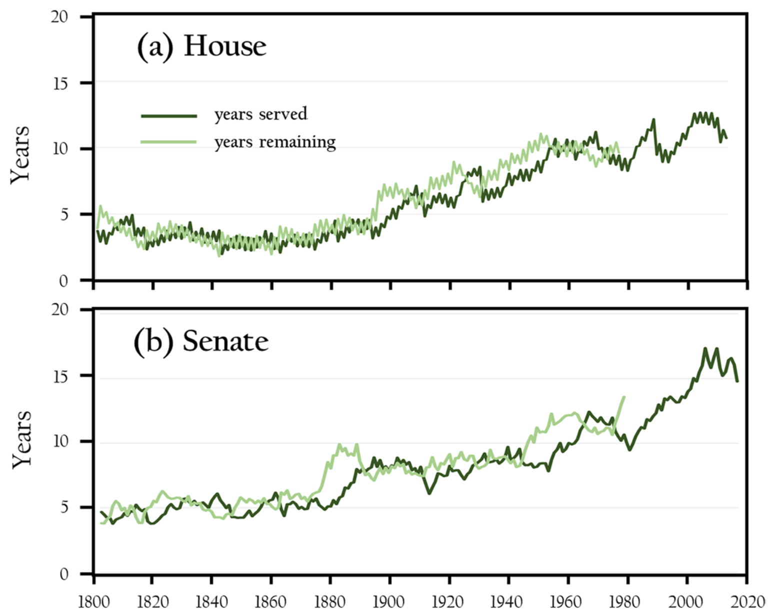

Fig. 3 Average number of years served and years remaining from 1800 through 2020 in **a** the U.S. House (top); and **b** the U.S. Senate. Data on "years remaining" are truncated after 1980 since many of Senator's were not yet completed

30%, the shape of the two distributions are robust mirror images. This near-symmetry is supported by results presented in the next section.

Correlation analyses

Plots of the correlation coefficients, R^2, for the years served versus years remaining for the Senate and House memberships from 1800 through 1980 are presented in Fig. 5, with example plots for selected years presented in Fig. 6. With a few exceptions, the R^2 values for membership in both chambers of Congress were universally high throughout this 180-year period. Fewer than 5% of R^2 values were less than 0.90 and nearly three quarters of the R^2 values were 0.95 or greater.

Turnover

The results of our analysis of observed congressional turnover rates as well as the Exponential Model predictions are shown in Fig. 7a, b for half-life (50% turnover), 75% and 95% for both membership in both the House and the Senate. Several distinct patterns are evident in these plots.

First, in both Congressional chambers (House; Senate) and at all turnover levels, the number of years for the incumbent's replacement of their predecessors (computed from the distributions of years served) were, on average, fewer than the number of years required for the incumbent's replacements within each of the three turnover levels (computed from the distributions of years remaining). For example, the half-life (50% turnover) for the *predecessors* of the 100 Senate members in 1980 was 7.4 years while the half-life of the 1980 *incumbent* Senators was 9.4 years. Similarly, the half-life for the *predecessors* of the 435 House members in 1980 was 6.9 years while the half-life of the 1980 *incumbent* House member was 7.8 years.

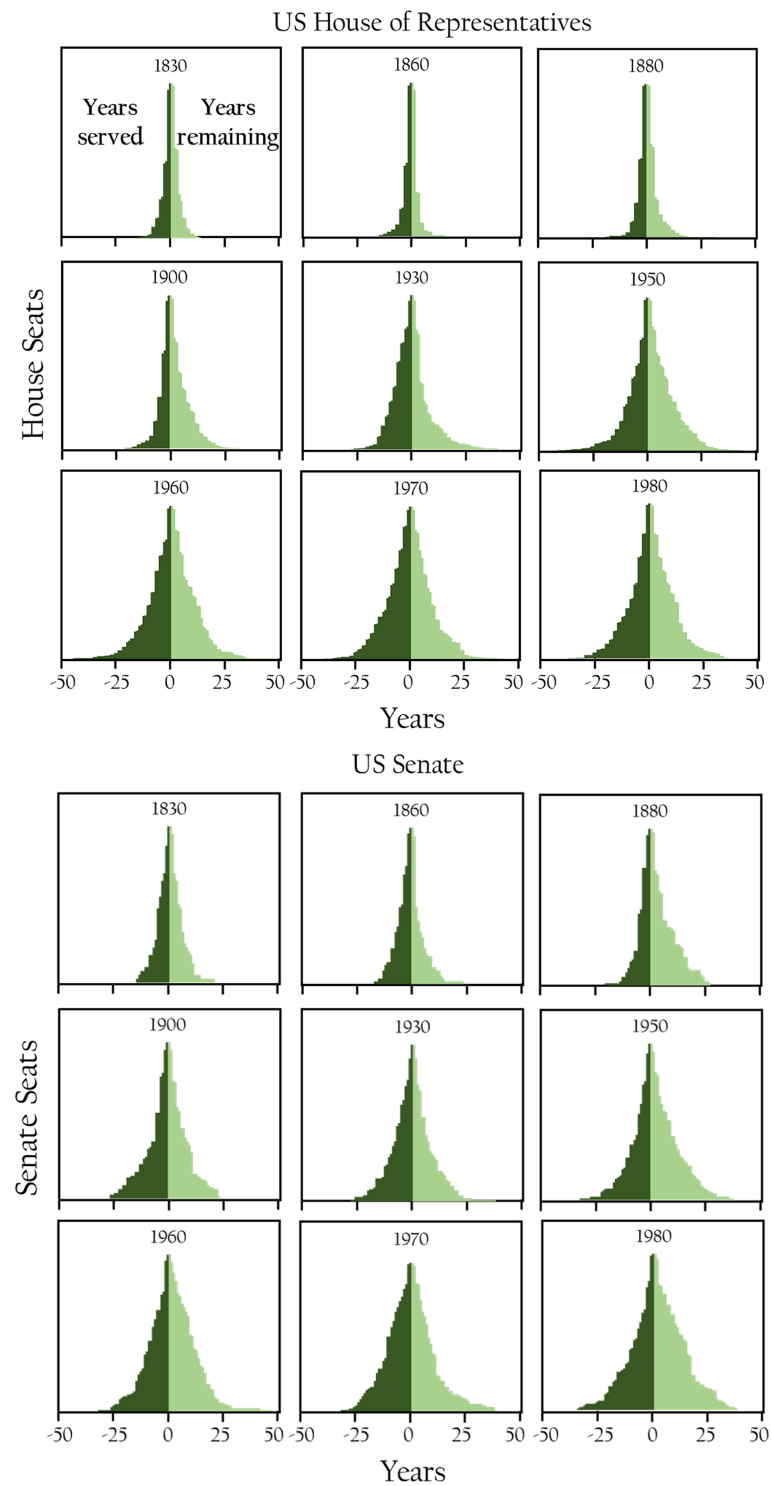

Fig. 4 Distributions of years served and years remaining for U.S. Senators normalized by number in selected years for the U.S. House (top panels) and Senate (bottom panels)

Second, in general the number of years required to turnover in the House were always fewer than for the Senate at all turnover levels. The 1980 half-life examples above illustrate this trend—7.4 and 9.4 year half-lives for the Senate and 6.9 and 7.8 year half-lives

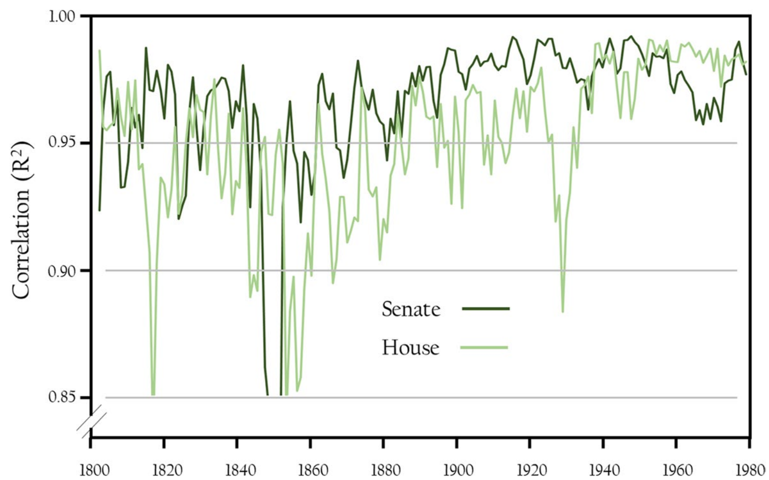

Fig. 5 Correlation coefficients (R^2) for the distributions for years served relative to years remaining in the U.S. House and U.S. Senate from 1800 through 1980

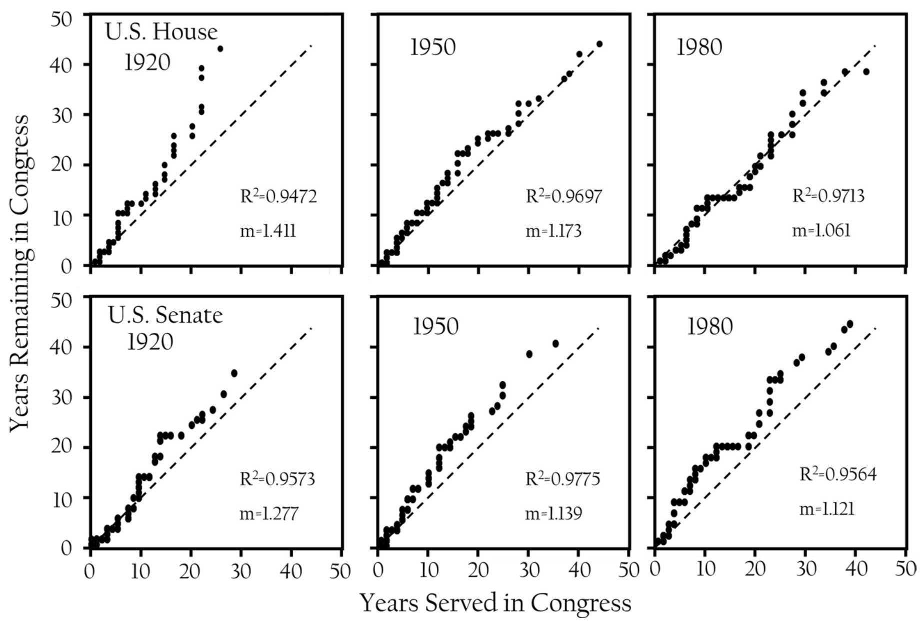

Fig. 6 Example plots of years served and years remaining for three selected years in the U.S. House (top row) and the U.S. Senate (bottom row). Complementary visual for Fig. 4

for corresponding distributions the House. Part of the reason for this almost certainly is the threefold difference in the lengths of the terms—i.e., 2 years for House members and 6 years for Senate members.

Third, the number of years required to turnover within each level was extremely short in the nineteenth century with the number of years required for turnover around 3 to 5 years for 50%, 5 to 10 years for 75% and 15 to 20 years for 95% for both the House and the Senate. In contrast, the number of years required to turnover within each level was substantially longer in the twentieth century with the number of years required for turnover around 5 to 8 years for 50%, 10 to 15 years for 75% and 30 to 45 years for 95% for both the House and the Senate. This sharp increase was

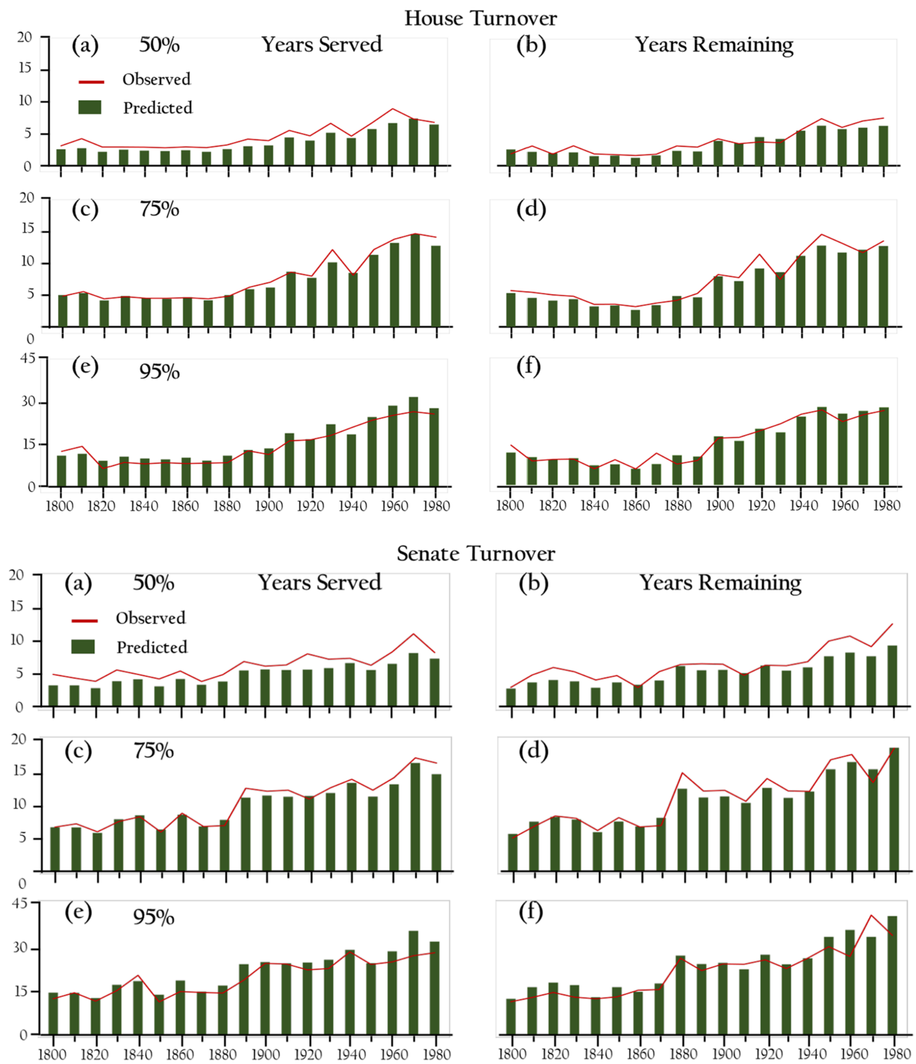

Fig. 7 Number of years required for 50, 75 and 95% turnovers in the U.S. House (top set of panels) and Senate (bottom set of panels) in 10-year intervals from 1800 through 1980 for years served (left columns) and years remaining (right columns). Bars indicate number of years predicted from exponential model using the inverse of the mean of the distributions for the rate parameter. The red line indicates the actual mean number of years actually served in the Congress during the specified year. Note the different *Y*-axis scale for the 95% levels

the outcome of the professionalization of Congress as incumbents ran for reelection more frequently and reelection rates were generally quite high.

Fourth, predictions of the Exponential Model using the inverse of the observed means for years served and years remaining as the exponential rate parameter were generally quite close to the observed rates for 75% and 95% turnovers. However, because of the convexity of the distributions at earlier years of service, the predictions were 1–3 years less than observed for 50% (half-life) turnovers for both the House and the Senate (Fig. 8). The convexity is shown in the distributions for the twentieth century and is particularly pronounced for the Senate.

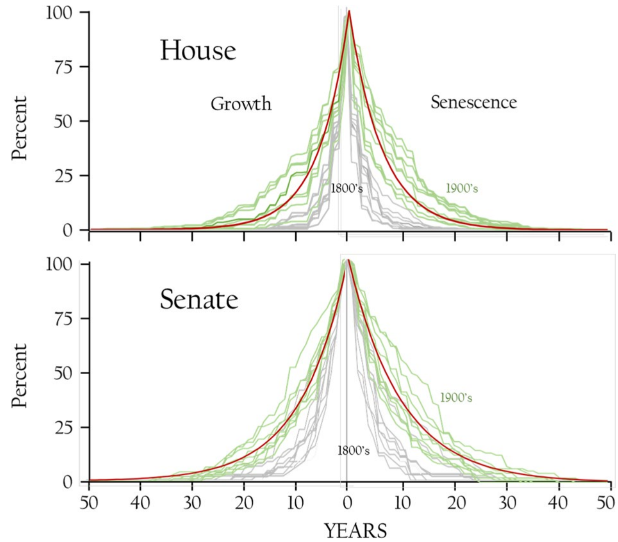

Fig. 8 Distributions of years served and years remaining in the U.S. House and Senate in 10-year intervals from 1800 through 1980. The red exponential curves were generated using the inverse of the mean-of-means for the nine distributions shown in green for the Congresses during the twentieth century, 1900 to 1980. Rate parameter values for the growth and senescence exponents of the House were 0.141 and 0.136, respectively, and for the Senate were 0.111 and 0.101, respectively

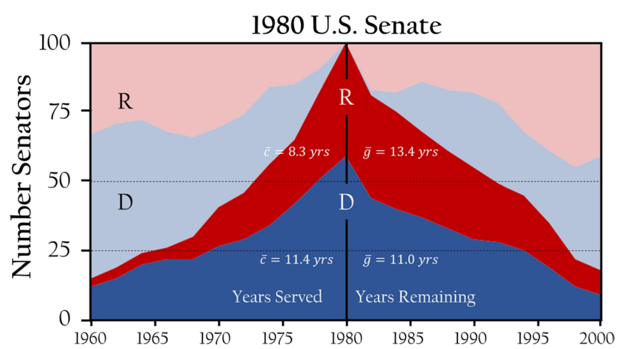

Fig. 9 Distribution of years served and years remaining by party affiliation for U.S. Senators in the 1980 U.S. Senate: Blue = 59 Democrats (D); Red = 41 Republicans (R). Note the average years served ($\bar{c}$) and remaining ($\bar{g}$) for members of each party. The light red and light blue-shaded regions on either side depict the proportion of the 100-senate seats filled by predecessors (on left) and successors (or right)

Party transitions

The CLC approach shifts both the computations and perspectives on Senate party affiliation transitions from the cross-sectional for evaluation of change in one or more election cycles to the longitudinal when considered across the 70 or more years of a complete Congressional life cycle. In the former the nature of change in the entire House or Senate membership from one election cycle to the next is considered, i.e., cross-sectional analysis of a combination of incumbent members who continue in office and new members who replaced former members. In contrast, for the latter the nature of change in the formation, growth, senescence and extinction of the incumbency is considered, i.e., longitudinal analysis of *only* members currently in office.

Here, we use the 1980 US Senate membership (Fig. 9) to illustrate both the concept and the approach for the seat transitions of each incumbent member—the first during the growth phase (i.e., the party of predecessor TO the party of incumbent) and the second during the senescence phase (i.e., the party of incumbent TO the party of successor). All transitions can have two outcomes including from-and-to the same party (retain) and from-and-to the opposing party (flip). Inasmuch as the years served and years remaining usually span three or more decades, the outcomes may span 70, 80 or more years.

The 2×2 transition tables for each phase are contained in Table 1A–C. The subtotals in the bottom rows and right-hand columns contain the party starting and ending number for each set of transitions. For example, the 57 D and 43 R predecessor seats (Table 1A bottom row) transitioned to nearly the same distribution—i.e., 58 D and 42 R. However, the seats of these incumbents transition to exactly the same distribution except flipped (Table 1B)—i.e., 42 D and 58 R.

Table 1 Three sets sub-tables containing numbers of party transitions for the 100 members of the 1980 U.S. Senate during the growth (first elected) and senescence (senate departure) phases

A. Growth phase

		FROM (predecessors)		TOT
		D^1	R^1	
TO (incumbents)	D^2	27 (DD)	31 (RD)	58
	R^2	30 (DR)	12 (RR)	42
	TOT	57	43	100

B. Senescence phase

		FROM (incumbents)		TOT
		D^1	R^1	
TO (successors)	D^2	29 (DD)	13 (RD)	42
	R^2	29 (DR)	29 (RR)	58
	TOT	58	42	100

C. Cycle-level transition sequence

TO	TO	FROM			
		D^1	R^1		
D^2	D^3	12 (DDD)	17 (RDD)	29	59
	R^3	16 (DDR)	14 (RDR)	30	
		28	31	59	
R^2	D^3	9 (DRD)	4 (RRD)	13	41
	R^3	20 (DRR)	8 (RRR)	28	
		29	12	41	
					100

D and R denote Democrat and Republican, respectively, and the transition direction follows from their order in the 2×2 tables with the superscript indicating the sequence order. For example in sub-Tables A and B, D^1D^2 denotes "from Democrat to Democrat" and R^1D^2 denotes "from Republican to Democrat". Thus in the growth phase of the 1980 Senate 27 Democrats replaced their Democrat predecessor (DD) and 31 Republicans were replaced by Democrats (RD). Sub-Table C contains the transitions across the entire life cycle. The superscripts again indicate the order. $R^1D^2D^3$ indicates the successor's, incumbent's and successor's parties were R, D and D, respectively. Thus 17 seats were flipped by the D incumbents who, in turn, were replaced by another D

Table 2 Transition metrics during growth and senescence phases for 100% turnover of the 100 members of the 1980 U.S. Senate

Notation	Description	Formula	Value (%)
Growth phase			
RET^{G}_{DD}	% of 1980 D senators who held onto their party's seat when first elected	$\frac{DD}{(DD+DR)}$	47.4
RET^{G}_{RR}	% of 1980 R senators who held onto their party's seat when first elected	$\frac{RR}{(RR+RD)}$	27.9
$RET^{G}_{DD/RR}$	Total party seat retention rate	$\frac{DD+RR}{(DD+DR+RR+RD)}$	39.0
FLP^{G}_{RD}	% of 1980 D senators who flipped their party's seat when first elected	$\frac{RD}{(RD+DD)}$	53.4
FLP^{G}_{DR}	% of 1980 R senators who flipped their party's seat when first elected	$\frac{DR}{(DR+RR)}$	71.4
$FLP^{G}_{DR/RD}$	Total party seat flip rate	$\frac{DR+RD}{(DD+DR+RR+RD)}$	61.0
Senescence phase			
RET^{S}_{DD}	% of 1980 D senators whose replacement held onto their party's seat	$\frac{DD}{(DD+DR)}$	50.0
RET^{S}_{RR}	% of 1980 R senators whose replacement held onto their party's seat	$\frac{RR}{(RR+RD)}$	69.0
$RET^{S}_{DD/RR}$	Total party seat retention rate	$\frac{DD+RR}{(DD+DR+RR+RD)}$	58.0
FLP^{S}_{DR}	% of 1980 D senators whose seats were flipped to R by their successor	$\frac{DR}{(DR+RR)}$	50.0
FLP^{S}_{RD}	% of 1980 R senators whose seats were flipped to D by their successor	$\frac{RD}{(RD+DD)}$	31.0
$FLP^{S}_{DR/RD}$	Total party seat flip rate	$\frac{DR+RD}{(DD+DR+RR+RD)}$	42.0
Complete two-transition cycle			
$CPLT^{F}_{DDD}$	% of 1980 D senators who replaced and were replaced by D	$\frac{DDD}{TOT}$	12.0
$CPLT^{F}_{RRR}$	% of 1980 R senators who replaced and were replaced by R	$\frac{RRR}{TOT}$	8.0
$CPLT^{F}_{DDD/RRR}$	% of 1980 senators who replaced and were replaced by member of same party	$\frac{DDD+RRR}{TOT}$	20.0

Senator-years totaled around 1100 or the equivalent of approximately 180 6-year terms (i.e., positive outcome elections). RET and FLP denote retention and flip, respectively, and superscripts G and S denote Growth and Senescence Phases, respectively. See Table 1 legend for formulae notation

The within-phase transition details are presented in Table 2, the contents of which reveal the nature of this reversal. The most telling metrics for why the party distributions remained nearly identical to those of their predecessors are from the Growth Phase: i.e., nearly half (47.4%) of the in-coming D Senators retained the seat's party affiliation and slightly over half (53.4%) flipped their seat affiliation from R to D. Likewise, the most telling metrics for why the party distribution then completely flipped numerically are these from the Senescence Phase: i.e., nearly 70% of R Senators retained their seat's party affiliation and exactly half of D seats were flipped to R seats. A total of 20 seats were controlled by one party over the nearly 75 years of the 1980 Senate life cycle including 12 seats D-to-D-to-D; 8 seats R-to-R-to-R (Table 1C).

Discussion of results

The historical data on the years served by members of the U.S. Congress that we used in this paper have, of course, been curated, analyzed, investigated, summarized, modeled and graphed by many hundreds if not many thousands of other researchers before us. A small sampling of these previous efforts is contained in the relatively recent publication titled "Congressional Careers: Service Tenure and Patterns of Member Service, 1789–2019" and the many books, journal articles and reports cited therein (Eckman &

Wilhelm, 2021). It follows that some of our results are not at all new. For example, the trend in increasing length of service by Congress members has been known for many decades (Eckman & Wilhelm, 2021, Open Secrets, 2020, Struble, 1979) as has the underlying cause as due to the increasing professionalization of politicians—the outcome of the combination of the desire of incumbents to serve in the House for long periods and the ability to be reelected (Brady et al., 1999; Hibbing, 1991).

However, we believe many of our findings and perspectives are indeed new, not only with respect to insights into the data on Congress, but also with respect to basic demography as generalized concepts and/or methods. We consider these original findings in two categories according to their *specificity* and *breadth* and follow with a subsection on the depth and scope of the Congressional Life Cycle model.

Specific findings

Symmetry of years served and remaining

The SPI model divides the total Congress-years into two segments: (1) their manifest past (years served); and (2) their latent future (years remaining). Although demographers have long known that the mean age of a hypothetical stationary population equals the average expectation of life of its members, connecting the respective distributions to create a model of reciprocity as we do in this paper is new.

Predictability and forecasting

It follows from the symmetry of the years served and remaining that one distribution can be predicted with knowledge of the other, at least as a relatively close first approximation. As we noted earlier this was evident both graphically (Fig. 5) and statistically (Fig. 6).

Extraordinary information content of years served distribution

Because of the robust symmetry, the consequent predictive capacity of the years served and remaining distributions and their historical uniformity over many decades, the information content of a single distribution—the number of years served in Congress—is extraordinary. This information alone constitutes the equivalent of a life table population from which all life table parameters can be computed including cohort survival (l_x), period survival (p_x) and mortality (q_x), death rate (d_x) and expectation of life at age x (e_x). The value of the inverse of the mean age in the population defines birth and death rates.

Simple exponential model fit for 230 years of congressional history

Some of the most important models in science are also often some of the simplest. As Fowler states (p3 in Fowler, 1997) "…one usually aims to oversimplify; the idea is that if a model is basically right, then it can subsequently be made more complicated, but the analysis of it is facilitated by having treated a simpler version first". Few mathematical models are more simple than the single-parameter Exponential Distribution Model that can be parameterized with a single number—the inverse of the mean number of years served (or remaining). This model fits the years served and remaining distributions remarkably well including the use of its rate parameter for computing quantiles such as Congressional half-life.

Party seat incumbent transitions

There are multiple categories of churn or turnover for a Congressional life cycle, the most prominent and most important being the party member seat turnover (Schaeffer, 2021)—(1) FROM predecessor TO incumbent; and (2) FROM incumbent TO successor. The two 2×2 sub-tables presented in Table 1 summarize the ultimate turnover fates of all members of Congress who are seated during a given year. However, there are potentially many additional classifications of turnover, e.g., gender (Slegten & Heyndels, 2021), minorities (Fraga & Hassell, 2020). A total of 20 seats were controlled by one party over the course of the nearly 75 years of the 1980 Senate life cycle (12 Democrats; 8 Republicans).

Broad findings

Congressional turnover and half-life

Whereas the conventional turnover metrics used in political science include the 12-year turnover (Struble, 1979) and percentage change by election (François & Grossman, 2015), the concept of Congressional half-life that we introduce in our paper could be considered a complemental metric. This is because half-life is a universal concept with applications in disciplines ranging from nuclear physics (Lucas & Unterweger, 2000) and pharmacology (Buckley, 2007) to medicine (Barzaman et al., 2020) and knowledge studies (Arbesman, 2012). We introduce the concept of Congressional half-life in the context of (50%) turnover, not only because it is so widely used, but because the concept (1) flows seamlessly from our study both from the historical data and the exponential model; (2) is simple, transparent, straightforward, intuitive, easily computed and readily compared; and (3) is a quantile metric and therefore computations for any turnover rate from 0.1 to 99.9% can be easily computed by substituting the turnover level of interest into the same mathematical formula. For example, the formula for the years required for Congress to turn over by 95% is simply $\frac{\ln(0.05)}{d}$. Similarly, the turnover fraction for T years, denoted TRN_T is computed from the equation $\mathrm{TRN}_T = e^{-dT}$. For example, if the mean years served in Congress is 8 years, then its inverse is $d=0.125$. Therefore, the 12-year turnover rate, TRN_{12}, equals $e^{-0.125\times 12} = 0.223$. In other words, slightly over one-in-five Congress members will still remain in office after 12 years.

Nested election cycles

A period-specific Congress can be conceived as an election Congressional Life Cycle within which are two nested sub-cycles—the 2-year constitutionally defined election cycle nested within the 6-year staggered-term Senate election cycle. Although the length of the Congressional Life Cycles varied historically for both the House and the Senate, in the late twentieth and early twenty-first centuries each lasted around 80 years—i.e., the length of time between the year the first member was elected through the year when the last member left office. This implies that there are approximately 14 Senate and 40 House election cycles per Congressional life cycle. With the number of years served by 100 Senators and 435 House members averaging around 12 and 10 years, respectively, each Congressional life cycle consists of a sum total of around 1200 Senator-years and 200 cumulative Senate-cycles and nearly 4350 House member-years and 2175 cumulative House-election cycles. On average approximately half of the years and the cycles will have occurred before (years served) and half after (years remaining) the specified period. It follows that the output of the life cycle model involves career-length metrics (combining years served and remaining) rather than partial career metrics (only years served) as is the case with conventional analyses in which a member's future service is not included. Longitudinal research similar to our approach serves two primary purposes: (1) to describe patterns of change; and (2) to establish the direction and magnitude of cause relations (Menard, 2002). The approach captures "the big picture" by offering descriptions of population characteristics making possible the modeling of longitudinal processes (Hauser & Weir, 2010).

Political viewpoints

The election cycle background provides perspectives on the depth of several of the metrics we presented earlier but separately. Here we describe three model output scenarios in a more unified context. (1) Political momentum. In 1980 the Democrats held the numerical advantage in the Senate (i.e., 59 D vs. 41 R). However, the Republicans held the momentum advantage—i.e., the average number of remaining terms (2.5 terms for R vs. 1.4 terms for D) and the duration of their membership half-life (i.e., 13 years for R vs. 10 years for D). This electoral momentum was an early (albeit retrospective) harbinger of a deeper and longer-term political trend—Congressional shift over the life cycle from majority of Democrats to either party parity or majority Republican as well as to Congressional polarization (Hillman, 2017; Neal, 2020); (2) Half-life of votes. If 100% of the 41 Republicans in the 1980 Senate voted against gun control as party-line votes, then 30, 20, 10, 5 and 1 vote(s) against gun control were carried forward to the 1985, 1991, 1997, 2009 and 2019 Senates, respectively. The last voting member of the 1980 Senate left office 74 years after one of its members first took office (in 1945). The same concept of vote "lifespans" would also apply to the "lives" of ideological camps (Poole & Rosenthal, 1997); (3) competitive versus safe seats. Not only did the years remaining for the 1980 Senate Republicans greatly exceed that for their Democrat counterparts, when these 41 Senators eventually left office their replacements were twice as likely to be from the same party than were Democrat's replacements—i.e., the Republicans flipped 29 Democratic seats in the Senescence phase of the life cycle whereas the Democrats flipped only 13 Republican seats when transitioning out of office. Thus the combination of flipped seats, higher rates of both seat retention during seat transitions and higher reelection rates (i.e., reflected in greater years remaining) foreshadowed the Congressional shift towards Republicans.

Perspectives and implications

Congressional

While in a typical year member reelection rates are nearly guaranteed, these figures portray a misleading image of constancy. Congressional turnover rates indicate the much more transient nature of membership structure. Turnover is of interest in a number of different Congressional contexts including social capital (Coleman, 1988; Jackman & Miller, 1998), institutional memory (Corbett et al., 2018), and term limits (Cain & Levin, 1999). As Matland and Studlar (2003) note, understanding change in legislative personnel is important for theories of elite circulation, for grasping how leadership opportunity structures develop, and for studying changing positions in public policy. The circulation of elites strengthens legitimacy and allows new ideas to spread. Analyzing this circulation from the perspective of broad institutional modeling provides a new angle with which researchers can visualize and track how cohorts of elites bleed into, and thus cultivate and train, new generations of policymakers.

The average "career lifespan" of both the House of Representatives and the Senate has varied since 1789. In Congress's early years, membership turnover was a frequent occurrence (Eckman & Wilhelm, 2021), but over the course of the nineteenth and twentieth centuries, the length of Congressional careers has increased (Brady et al., 1999). The professionalization of Congress since the nineteenth century significantly increased reelection campaign rates. Whereas prior to the Civil War, typically 40% of representatives would not seek reelection, today only approximately 11.5% forgo reelection The average years served in the 117th Congress was 8.9 years in the House and 11 years in the Senate. In the aggregate, then, careers are much longer than they were before (Eckman & Wilhelm, 2021). However, when combined with current turnover rates, there still remains considerable variation in Congressional experience, which impacts the development of Congressional cohorts and the spread of institutional wisdom.

There are many contexts that likely have shaped these structural trends of the US Congress. For example, the importance of seniority within Congress and the increased importance of federal policymaking since the nineteenth century likely act as intrinsic and extrinsic factors shaping decisions to either run for reelection or retire. This, in turn, plays a role in the development of Congress's generational entry points, as well as the socialization of the cohorts. But structure itself has an impact. The breakdown of Congressional experience in a given Congress itself indicates the potential for norms and processes of the institution to be spread to newer members. In turn, newer members are placed in particular contexts within which they develop cohorts and adversaries. In measuring cycles of terms served and terms left the Congressional Life Cycle Model helps illuminate how these career lifespans map onto moments of generational entry points—and thus likely cultural breaks or shifts in Congressional dynamics—as well as helps to visualize how institutional wisdom, norms, and cultural processes are shared over time.

This dynamic comes with significant consequences. Over two-thirds of the House and nearly two-thirds of the Senate have held office for less than 12 years (DeSilver, 2022). In a world where the average member of Congress has served less than a decade, many representatives become educated in institutional worlds that may look far different than the world only 10 years before. Take, for example, how the appropriations process has changed since 2010, the last fiscal year in which an appropriations bill was signed into law before its October 1 deadline. Over half of the current Congress only began serving after this fiscal year, and have been professionally trained over the course of their tenure in a world of norms and cultures far different from the one witnessed in the first decade of the twenty-first century. As these members gain seniority, the experience gained as part of this period and its socialization will likely be carried into the education of future members, who will serve and may carry on these particular appropriations lessons beyond current members' career lifespans.

High reelection rates are not enough to understand the quantitative and even qualitative realities of the US Congress. Retirements leave their marks. What rates of turnover alone miss is how the ends of individual careers may leave aspects of institutional memory forgotten. In conceptualizing the terms served and terms remaining model provided by the Congressional Life Cycle scholars can better identity generational entry points and periods of potential cohort-building and mentorship. Put differently, the model not only measures particular moments of experience and tenure, but also visualizes when generations—and the logics they held—rise and fall. It illuminates conceptions not just of changing institutional structures, but of the changing periods of old institutional cultures and the developing points of the new.

Turnover rates peaked in the late 1970s and early 1980s (DeSilver, 2022), which may indicate a period of great generational—and thus institutional—change. Other potential generational entry points may be in the high turnover elections, including 1872, 1890, 1894, and 1932. Between redistricting and a wave of retirements, the 2022 midterm elections may be another generational turning point. While previous studies (Eckman and Wilhelm, 2021) have rejected the predictability of Congress's changing tenure patterns, the SPI model potentially provides a predictive model of institutional development that can estimate the rough experience structures of future Congresses.

Demographic

In this paper, we built upon and extended much of the earlier work on stationary population theory. This includes the seminal work of Norman Ryder who laid out the formal requirements for stationarity including fixed survival and maternity functions, a value of unity for the product (i.e., net maternity), and closed to migration (Ryder, 1973, 1975). Other previous work on stationary theory includes the formal mathematics quasi-stationary populations (e.g., Barbour, 1976; Méléard & Villemonais, 2012; Pollett, 2001; van Doorn & Pollett, 2013) and quasi-stationary population persistence times when subject to limiting resources (Méléard & Villemonais, 2012; Pollett, 2001; van Doorn & Pollett, 2013). Rao and Carey (2019b) introduced related concepts concerned with stationary populations including *transient stationarity* and *oscillatory stationary population identity* as well as populations that are *predominantly stationary*—i.e., populations that are essentially at replacement-level growth but which switch between positive and negative growth. This intermittency of positive and negative growth averaging zero growth would fall into the category of zero population growth that Cohen (1995) referred to as "weak", a concept asserting that a long-term average global population growth rate of zero is unlikely to apply universally to every region at every time (also see Bricker & Ibbitson, 2019; Skirbekk, 2022).

The assumption of population stationarity has been used for many decades in estimates of survival rates using skeletal estimates of age in anthropological and archeological as well as with the use of cemetery data when accurate information on age of death is available (Barbiera et al., 2018; Love & Müller, 2002; Wood et al., 2002). Similarly estimating survival probabilities in populations of slow-growing, critically endangered species are implicitly framed by a quasi-stationarity assumption (Weiss & Wobst, 1973), examples of which include mountain gorillas (Granjon et al., 2020), black rhinoceros (Ferreira et al., 2011), and whooping cranes (Gil-Weir et al., 2012). The assumption of long-term zero population growth is also often used in the context of cycling populations such as with wolves and moose (Peterson & Page, 1988), lynx and hare (Brand et al., 1976) arctic reindeer (Klein, 1968).

The SPI model builds on and extends the concepts on stationary populations that Preston et al (2001) brought together in their book regarding the interconnectedness of parameters of expectation of life, birth, death and age structure. Whereas the relationship between the mean age in a population and the expectation of life of the average member has been understood for many years (Goldstein, 2009; Kim & Aron, 1989; Ryder, 1975), the SPI rendered manifest the equality of the underlying distributions upon which the means were based—i.e., the age distribution and the distribution of remaining lives are equal in stationary populations. This equality then set the stage for making comparisons, not only between averages, but between their underlying distributions.

We believe that virtually all of the findings on Congress are potentially generalizable and thus can be applied across a wide range of population contexts. We also believe that they are especially relevant to studies of human populations that are near stationarity, which is to say, many countries now and nearly all in the future (Coleman & Rowthorn, 2011; Lutz et al., 2001; United Nations 2019a, 2019b).

Conclusions

To our knowledge, ours is the first paper to bring stationary population theory to bear on data, the perspective heretofore having been that the models are purely hypothetical because no truly stationary populations exist in the real world. By conceiving the historical membership in the U.S. Congress as stationary populations, we were able to demonstrate the heuristic and practical utility of the Stationary Population Identity model. Our analysis in this paper was not about bringing standard demographic concepts and methods to bear on data from an area traditionally outside of demography, in this case Congressional membership data from political science. Instead we did the reverse by bringing data from the U.S. Congress to validate new demographic theory and at the same time attempted to cultivate both theory and empiricism side-by-side as described by one of the twentieth century's seminal figures in demography, Lotka (1938). Lotka believed this approach described the "ideal process" in which empirical data provide concrete illustrations of the abstract principles and the formal relations serve as guides in the examination and interpretation of the empirical data.

Appendices

Appendix 1: U.S. House of Representatives and Senate

The U.S. House of Representatives and the U.S. Senate were established by the U.S. Constitution with the number of members conditional on number within each state for the former (lower chamber) and two members representing each state in the latter (upper chamber). Congress first met as in 1789 with 59 members from 11 states (expanded to 65 the next year with representatives from two other states) in the House 26 members from 13 states in the Senate. A total of 35 new states and thus new Congressional members were added over the next 123 years to bring the total to 48 states in 1912. Two additional states were added in 1959 including Alaska and Hawaii. In 1929 the number of Representatives was capped at 435. (The U.S. House of Representatives 2022; The U.S. Senate, 2022).

Appendix 2: Risk in electoral context

Analytical perspectives related to the likelihood of an individual serving in a Congressional seat typically include a set of metrics (Congressional Research Service, 2019) such as percentage seeking re-election, percentage retiring, percentage seeking different office, percentage re-elected and percentage defeated. Although these metrics are straightforward and intuitive, their collective conceptual, actuarial and statistical congruency can be improved by framing them with respect to risk-of-departure.

As an example, consider the re-election rates percentages for members of the House of 90.6 and 78.6% for 2000 and 2018, respectively (Tables 2.7 and 2.8 in Brookings, 2021). Whereas their difference is 12% and their ratio (former-to-latter) is over 1.2, there exists a 2.3-fold difference in the incumbent's re-election loss probabilities between the two elections—i.e., equal to the ratio of their risk complements that express the probability of re-election *loss* (i.e., 9.4% and 21.4%). This is not a statistical sleight-of-hand to exaggerate perspective or scale, but rather an analytical necessity for situating election probabilities in the domain of the statistical and actuarial sciences (Land et al., 2005).

The basic role of exit risk or failure rate (i.e., using mortality as metaphor) as illustrated above is evident by considering the following paraphrasing of mortality in the parlance and context of elections (Carey & Roach, 2020; Carey et al., 2018). *First*, losing an election is an event that underlies a politician's change-of-state from the state of incumbency to the state of non-incumbency. The concept of events as changes of state (e.g., live-to-dead; incumbent-to-non-incumbent) is fundamental to the analysis of risk and actuarial analyses. *Second*, an incumbent can exit their seat in Congress due to a number of causes such as by losing an election, by retiring, by expulsion or by dying. Therefore, exit rates can be disaggregated by any of these causes. It follows that cause-elimination life table models can be brought to bear on "what-if" questions regarding the impact on membership turnover of, say increases in retirement rates versus decreases in incumbent re-election rates (Ledent & Zeng, 2010; Preston et al., 1978). Although there are obviously underlying conditions for why individuals continue to live, an analogous concept to "cause of death" does not apply to continuation in office any more than it applies to the continuation of living. *Third*, a number of different mathematical models of risk have been developed (e.g., Gompertz, Weibull) that provide simple and concise means for expressing the actuarial properties of cohorts using only one or two parameters (see Chpt 3 in Carey & Roach, 2020).

Just as in the demographic analysis of underlying causes of death in which multiple causes interact and thus are not independent, there are also analogous situations in elections. For example Congressional Member decisions to seek reelection and whether or not the Member is defeated for reelection are tied to one another. The decision to seek reelection may be based, in part, on an estimate of the likelihood of success. Accordingly, a decrease in the percentage of Members who are defeated for reelection may be indicative of greater trends, but in some cases may reflect an increase in Members choosing not to stand for reelection when their reelection prospects are diminished (Brady et al., 1999; Congressional Research Service, 2019; Hibbing, 1991; Stone et al., 2010).

Appendix 3: Visualizing congressional turnover rates

See Table 3 and Fig. 10.

Table 3 Years required for 50, 75 and 95% membership turnover in the 1980 U.S. Senate in the Growth and Senescence Phases of the population life cycle model including years observed as well as years predicted by the Exponential model using the inverse of the means as the exponential rate parameters

Turnover level	For growth phase (years)		For senescence phase (years)	
	Observed	**Model**	**Observed**	**Model**
50%	7.2	7.0	11.7	9.1
75%	15.5	15.9	18.5	18.1
95%	27.1	30.2	33.0	39.2
Mean	10.2	10.2	13.1	13.1
Rate parameter	0.098	0.098	0.076	0.076

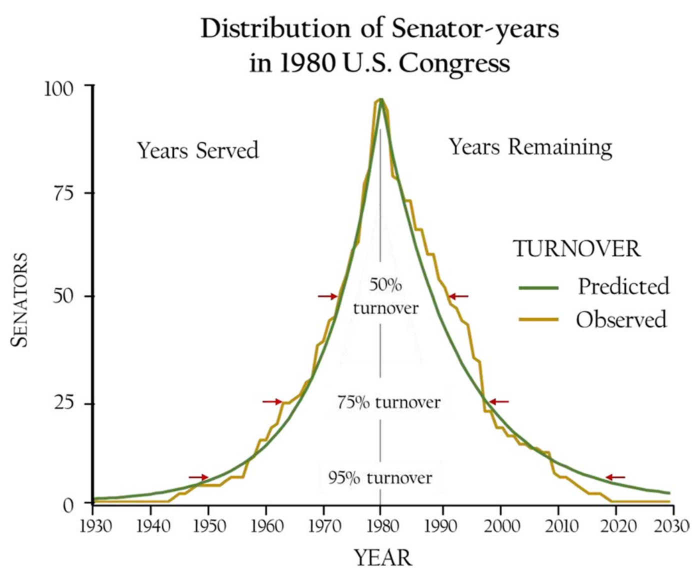

Fig. 10 Observed and predicted distributions of the years served and the years remaining for members of the 1980 U.S. Senate. Predicted distributions were based on the inverse of the means of years served and predicted as the exponential rate parameters. Note the small differences between the observed and predicted distributions for year served but the differences between these distributions for years remaining. This graphic sheds light on why some differences exist between observed and predicted means in Fig. 7a, b

Appendix 4: Video animation

Distributions of years served and years remaining for members of the U.S. Senate, 1800 to 1980.

Click Here

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Author contributions

JRC led the study conceptualization, manuscript writing, data analysis, creation of figures and video scripting and production. BE led the study literature search and review and assisted with writing; ASRSR contributed to study conceptualization and critique. All authors read and approved the final manuscript.

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Data availability

All data were downloaded from GovTrack (2022)—a website containing historical lists of members of congress: https://www.govtrack.us/congress/members/all#all_role_types=2.

Declarations

Competing interests

The authors declare that they have no competing interests.

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