State-Level Decision-Making In Cyclus to Assess Multilateral Enrichment

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Abstract

Proposed treaties and agreements that aim to reduce the spread of nuclear weapons are often stalled by skepticism regarding their efficacy. For example, the concept of multilateral enrichment, in which multiple states co-own and operate an enrichment facility, has the potential to reduce the spread of enrichment technology. However, detractors point to the improved international networking opportunities inherent in multinational organizations as a risk factor for increased proliferation. A framework to compare the relative risk between a multilateral enrichment paradigm and the status quo, on a regional scale, can help inform the discussion and potentially identify ways to reduce global risk of nuclear proliferation. As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used as a test-bed for the development of such new technologies and approaches to treaty verification. Cyclus is a systems-level nuclear fuel cycle simulator that models the interactions between actors in the nuclear arena. While designed to track the flow of nuclear material between facilities, Cyclus also incorporates an innovative Region-Institution-Facility hierarchy that can capture the dynamics of state-level interactions. Drawing on social science literature to identify factors that motivate states to pursue weapons programs, we have developed a regional proliferation model that captures causes and effects of state-level nuclear weapons proliferation. The model identifies eight key factors that influence a states decision to pursue nuclear weapons. These factors include motivations internal to the state, such as military spending and governing structure, as well as interactive factors such as conflict between states. Historical data is used to identify the relative importance of these factors and translate them into a likelihood of pursuing a weapon. The model also provides a feedback mechanism such that acquisition of a nuclear weapon by one state influences the decision-making of the other states. This model will be used to assess the effectiveness of policy approaches, such as multilateralization of the fuel cycle, that seek to reduce the regional risk of proliferation over time.

1 Introduction

Progress in preventing the spread of nuclear weapons is contigent both upon limiting access to the required technology as well as disincentivizing weapons programs. An effective global nonproliferation regime must synthesize knowledge from the realms of political science, international relations, nuclear physics and engineering, and even behavioral psychology. An understanding of when and why states proliferate can inform future treaties and agreements to minimize this risk. For example, the concept of multilateral enrichment, in which multiple states co-own and operate an enrichment facility, has the potential to reduce the spread of enrichment technology. However, detractors risks associated with international networking opportunities inherent in multinational organizations as a path for increased proliferation[1, 2]. A multi-state modeling framework to compare the relative risk between proposed treaty paradigms and the status quo can help inform the discussion and potentially identify ways to reduce global risk of nuclear proliferation.

As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used as a test-bed for the development of such new technologies and approaches to treaty development. Cyclus is a systems-level nuclear fuel cycle simulator that models the interactions between actors in the nuclear arena[3, 4, 5]. While designed to track the flow of nuclear material between facilities, Cyclus also incorporates an innovative Region-Institution-Facility hierarchy that can capture the dynamics of regional-level interactions between states. We have developed a forward model in which a set of hypothetical states can be given individual political and technical attributes. This model then tracks whether each state develops nuclear weapons over time based on how these attributes evolve in time, including feedback on conflict levels between states.

2 Factors That Correlate to Pursuit of Nuclear Weapons

Social science literature has suggested a variety of political and technical factors that may motivate a state to pursue nuclear weapons[6, 7, 8, 9, 10]. Political factors include: degree to which governing structure is authoritarian versus democratic, level of military spending, degree to which state is isolated militarily, and level of conflict with other states. Technical factors include: degree to which the state's scientific expertise is integrated into the international community, nuclear reactor experience, indigenous reserves of natural uraniaum, and the ability to enrich uranium.

We have compiled a database of information that quantifies each of these eight factors for states at important historical points, publically available on Github,[1] along with documentation on source data and assumptions[11]. The set includes 43 unique states that have historically had some level of nuclear energy or weapons technology. The 24 states that have never pursued weapons have data compiled for 2015. The 19 states that have pursued weapons at some point in the past have data for the year in which they pursued as well as the year in which they acquired a weapon, if applicable. Pursuit and acquisition dates are coded from *Singh and Way*[7]. The pursuit date is defined as the first year in which a significant decision to pursue nuclear weapons was made, such as a political decision by cabinet-level officials, movement toward weaponization, or development of single-use, dedicated technology. Acquisition date indicates the year of first explosion of a nuclear device or when a weapon was first assembled, since not all countries tested their nuclear weapons.

2.1 Pursuit Score

The source used to define each factor has been taken from social science literature and is listed in Table 1. The raw data for each attribute has been normalized on a 1-10 scale so that all factors can be compared directly, as described in Table 2. Conflict is shown separately in Table 3. Conflict has been defined for a given state by using the *Uppsala database* to identify up to three significant state-pair relationships based on the state's conflicts during that year (the dataset was limited to three as a starting point, but could be further expanded)[13]. Each of these relationships is coded as enemy, neutral, or ally. Each of the two states in the pair is also identified as being a Non-nuclear Weapons State (NNWS), pursuing weapons, or a Nuclear Weapons State (NWS). The relationship status and the weapons status of each pair are combined to provide a conflict score for the pair. The net conflict factor is then the average of all the state's paired conflict scores. We consider the pursuit phase as the most destabilizing, and have incorporated considerations such

[1] https://github.com/CNERG/historical_prolif

Factor	Source Database
Authoritarian	Center for Systemic Peace Polity IV Annual Time-Series, 1800-2015[12]
Conflict	Uppsala Conflict Data Program Armed Conflict Dataset[13]
Enrichment/Reprocessing	Nuclear Latency Dataset [14]
Military Isolation	Rice University The Alliance Treaty Obligations and Provision Project[15]
Military Spending	Stockholm International Peace Research Institute Military Expenditure Database 1949-2015[16]
Nuclear Reactors	IAEA Power Reactor Database [17] IAEA Research Reactor Database [18]
Scientific Network	Authors' Expert Opinion
Uranium Reserves	OECD Uranium: Resources, Production and Demand [19]

Tab. 1: Source data for each factor contributing to pursuit of nuclear weapons addressed in this paper. Scientific network assessment considers GDP, opportunities for scientists to study abroad, nuclear infrastructure, technical human capital.

as preventative war by nuclear states, consequences of a nuclear umbrella, and increased low-level conflict between weapons states [20, 21, 22].

Once every state has been assigned a 0-10 score for each factor (fs), a correlation analysis was applied to the derived factor scores to quantify the degree to which each individual factor is correlated to the decision of whether or not to pursue weapons. The resulting weight for each factor is derived from the Pearson correlation coefficient. The bivariate correlation (w_f) between the factor and the score is:

$$w_f = \frac{\sum_{i=0}^{N}(f_i - \bar{f})(s_i - \bar{s})}{\sqrt{\sum_{i=0}^{N}\left(f_i - \bar{f}\right)}\sqrt{\sum_{i=0}^{N}\left(s_i - \bar{s}\right)}}, \tag{1}$$

where N corresponds to the number of states, f_i and s_i to the individual factor and the total score of a given state i, respectively, and $\bar{f}$ and $\bar{s}$ to the mean factor and the mean score averaged over all states. The correlation coefficients are then normalized so that the final pursuit score for a state can be defined a weighted linear combination of its factors. The normalized weights of the 8 factors are listed in Table 4.

Final pursuit scores can range between 0 and 10. Confidence in the weights was confirmed by applying the weighted equation to the historical data and examining the degree to which scores accurately match historical pursuit decisions. Historically-based scores are shown in Table 5 for the year in which each state explored or pursued a weapon, or 2015 for states that have never developed weapons programs. The historical scores are consistent with the expectation that states that actually pursued weapons should have the highest scores (red), on average. It is important to note that this table shows the correlation between scores and pursuit, but does not imply causation. No conclusions can or should be drawn about the future actions of any NNWS that had a high score in 2015.

Two notable insights arise from this analysis. First, a state's reactor technology is anti-correlated to pursuing a nuclear weapon. Denoted in Table 4 with a minus sign for illustrative purposes, in practice the conversion for this factor has been inverted such that maximum number of reactors leads to a minimum reactor score, and so that the absolute value of the weight (18%) can used. Second, indigenous uranium

Factor Score (s_f)	**Auth**	**Enrich/ Repro.**	**Military Iso.** $10-(A_{NNWS}+A_{NWS})$		**Mil. Spend (%GDP)**	**Reactors** (Power+Research) $10-R_{all}$	**Sci. Net.**	**Uran. Res**
			NNWS	NWS				
0	0	0	–	–	–	0	–	0
1	1	–	1-2	–	<1	1-3 planned	–	–
2	2	–	3-4	–	[1, 2)	4+ planned	–	–
3	3	–	5+	–	–	–	–	–
4	4	–	–	–	[2, 3)	1-3 built	1	–
5	5	–	–	1	–	–	–	–
6	6	–	–	2	–	–	–	–
7	7	–	–	3+	[3, 5)	4-7 built	2	–
8	8	–	–	–	–	–	–	–
9	9	–	–	–	–	–	–	–
10	10	1	–	–	5.0+	8+ built	3	10

Tab. 2: Conversion from raw data to final factor score (s_f). Square brackets are inclusive, parentheses are exclusive, such that [1,2) indicates $1 <= x < 2$. Reactors and military alliances (used to define military isolation) are both anti-correlated to pursuit so those factor scores are 10 minus the value shown in the table. Conflict factor is defined separately in Table 3.

Nuc. Weapon Status	**Allies**	**Neutral**	**Enemies**
NNWS - NNWS	2	2	6
NNWS - Pursue	3	4	8
NNWS - NWS	1	4	7
Pursue - Pursue	4	5	9
Pursue - NWS	3	6	10
NWS - NWS	1	3	5

Tab. 3: Conflict score assignments are based on weapons status and relationship between pair states. Weapon status may be NNWS, pursuing weapons, or NWS. Relationship status is assumed to be symmetric and may be positive allies, neutral, or enemies.

Factor	**Weight**
Authoritarian	0.12
Conflict	0.26
Enrichment & Reprocessing	0.10
Military Isolation	0.075
Military Spending	0.21
Reactors	-0.18
Scientific Network	0.05
Uranium Reserves	0.0

Tab. 4: Relative weighting of each factor toward pursuit decision as determined by correlation analysis of historical data. Note reactor technology is anti-correlated and uranium reserve factor is uncorrelated.

State	Year	Pursuit Score
USSR	1945	**8.9**
Iran	1985	**8.3**
Iraq	1983	**8.2**
N. Korea	1980	**7.7**
Libya	1970	**7.4**
Egypt	1965	**7.3**
Syria	2000	**6.9**
France	1954	**6.8**
Algeria	1983	**6.6**
Saudi Arabia	2015	6.5
US	1942	**6.5**
India	1964	**6.4**
China	1955	**6.3**
UAE	2015	6.3
Israel	1960	**6.2**
Argentina	1978	**6.1**
S. Africa	1974	**5.9**
UK	1947	**5.8**
Pakistan	1972	**5.3**
Armenia	2015	5.0
Sweden	1946	**4.8**
Romania	1985	**4.5**

State	Year	Pursuit Score
Indonesia	1965	**4.4**
Switzerland	1946	**4.4**
Belarus	2015	4.4
S. Korea	1970	**4.4**
Brazil	1978	**4.3**
Australia	1961	**3.9**
Ukraine	2015	3.2
Kazakhstan	2015	3.1
Lithuania	2015	3.1
Japan	2015	3.0
Netherlands	2015	2.7
Finland	2015	2.5
Germany	2015	2.5
Bulgaria	2015	2.4
Mexico	2015	2.0
Slovakia	2015	1.8
Hungary	2015	1.6
Spain	2015	1.6
Czech Republic	2015	1.3
Canada	2015	1.2
Belgium	2015	1.0

Tab. 5: Historical scores calculated for states based on their factor values at the designated year. The factor weighting accurately results in high scores for states that explored, pursued or acquired nuclear weapons (bold red), and lower scores to those that never investigated a nuclear weapons program (black), on average.

reserves were uncorrelated to weapons programs. These two results were not predicted by the social science literature[9].

3 A Cyclus Model of Nuclear Weapon Pursuit

We have applied the factors correlated to pursuit of nuclear weapons in a regional model of state interactions using CYCLUS. The Computational Nuclear Engineering Research Group (CNERG)[2] group at the University of Wisconsin has developed the CYCLUS[3] nuclear fuel cycle simulator to model all aspects of the nuclear fuel cycle in a flexible way. CYCLUS has three key features: it is *agent-based*, it tracks *discrete materials*, and it incorporates *social and behavioral interaction models*[23, 24, 25]. This design allows customized facilities and institutions to engage in dynamic decision-making based on their preferences, needs, or political constraints across a wide range of scenarios.A region-institution-facility framework captures have preferences based on material composition, physical proximity between facilities, or preferred trading partners.

3.1 The Forward Model

The region-institution-facility design has been used to develop the Nuclear Weapons Pursuit Model (NWPM). This forward model features two custom archetypes, an interaction region and a state institution[26]. The state institution represents a nation-state and includes time-dynamic information about each of the pursuit factors. The interaction region is an omniscient presence in the simulation that tracks weapon status as well as interactive pursuit factors such as conflict (as described in section 2.1), and communicates that factor to each individual state.

Each of the motivating factors is defined for every state in a time dynamic way. Individual factors must have values between 0-10. There are several time dynamic parameterizations currently available in the model: constant, linear growth or decline, step-function (at either a specified or a randomly chosen time), or power-law. These functions enable modeling of characteristics such as growth in military spending, development of new technologies (such as enrichment), and sudden changes to factors such as governing structure or inter-state conflict. At each timestep, the state institution combines all of these factor values into a pursuit score using the weighted linear equation defined in section 2.

3.2 Likelihood

The pursuit score (s) is then converted into a likelihood that the state will pursue a weapon. The relationship between pursuit score and likelihood of pursuing a weapon has been characterized using historical data of the 43 states that have developed nuclear technology since 1942. Figure 1 shows the fraction of states with a given pursuit score that pursued a weapon at some point between 1942 and 2015. A power-law (red) or a linear fit (black) are equivalently valid with the 43 state dataset. However, a global dataset of nation-states will have disproportionately lower scores and zero additional incidences of pursuit, so we consider the power-law paramaterization to be more representative.

While the historical data provides the probability of pursuit integrated over 75 years (T), a single-year probability is needed for the forward model. A state can only choose to pursue in a given year (p) if it is

[2] http://cnerg.github.io/
[3] http://fuelcycle.org/

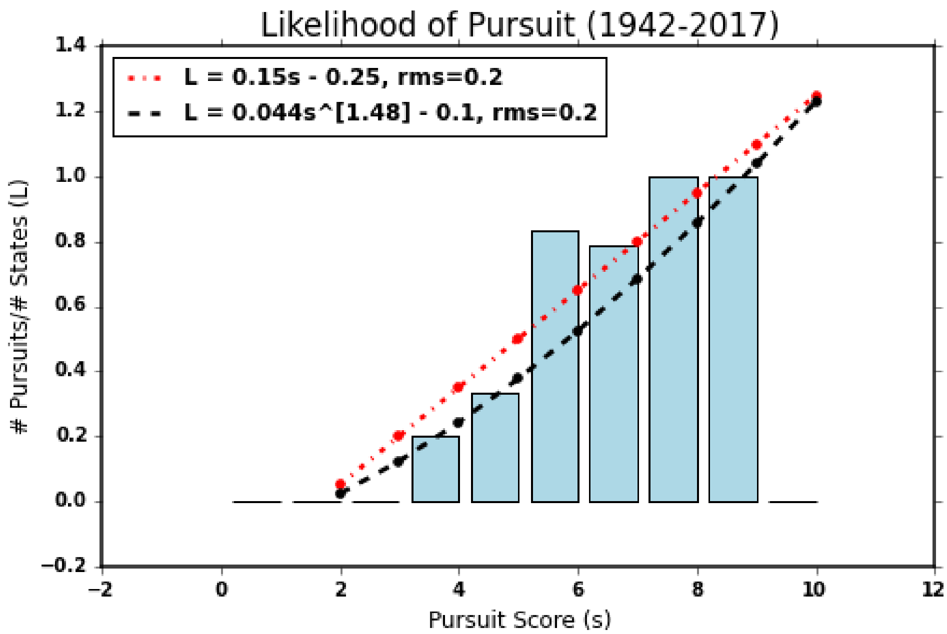

Fig. 1: Fraction of states with any nuclear technology (dataset from section 2) that pursued weapons at some point in the last 75 years, given their pursuit scores. Although a power-law curve (black) and a weighted linear fit (red) are equivalent with the existing data, a complete set of nation-states would increase the relative weight of lower scores, making the exponential curve a better fit.

not already pursuing, therefore probability must be defined by the absence of pursuit. The probability that a state will Not pursue in a single years is $1-p$. The likelihood of non-pursuit $\bar{L}$ integrated over N years is:

$$\bar{L} = (1-p)^N \tag{2}$$

And the likelihood of a pursuit (L) integrated over N years becomes:

$$L = 1-(1-p)^N \tag{3}$$

Therefore the probability of pursuit in a single year is:

$$p = 1-(1-L)^{1.0/N} \tag{4}$$

In the NWPM forward model, each state's score is converted to a single year probability of pursuit using the power-law fit shown in Figure 1. The actual conversion is bounded using two Heavyside functions such that scores below a lower threshold (e.g. 4) are forced to a likelihood of zero, while scores above an upper threshold (e.g. 9) are forced to the value of the score at that threshold. At each time in the simulation, a random number generator is queried using the score-derived probability (p) to determine whether or not the pursuit event occurs. If a model is provided for the likelihood of acquisition given pursuit, then acquistion is also tracked. Both pursuit and acquisition decisions then influence future conflict relationships with the other states.

4 Discussion: Limitations of the Framework

The use of historical data to develop a forward model has several limitations. The biggest limitation is in the size of this data set, both in terms of the number of states and in the range of years that are included.

With only 10 states that have acquired nuclear weapons in the historical record, there is large uncertainty in any quantitative analysis. As a result, while the analysis has identified factors that are correlated to weapons programs, there is insufficient data to confirm causal relationships.

Since the data set already includes all states that have pursued nuclear weapons, the missing states would only be relevant to the likelihood analysis if they had pursuit scores of 4 or larger, thus reducing the time-integrated likelihood of pursuit associated with such scores. Due to the influence of nuclear technology, a non-nuclear state could theoretically have a maximum pursuit score of 7. Considering that the majority of states that have high potential military spending and major historical conflicts have already been incorporated, this further reduces the potential maximum score to below 5, even if all other factors are maximized. A large fraction of states in the world are expected to have scores on the order of 1-3, and thus not alter the distribution shown in 1.

A more important addition to the database would be data for each state for all years between 1940 (before the first historical pursuit) and the year of pursuit and/or aquisition. This would allow the direct calculation of an annual probability of pursuit as a function of the pursuit score. The current model for converting a time-integrated likelihood to an annual probability inherently assumes that the pursuit score for the states in the data set is constant for all the years prior to the decision to pursue nuclear weapons. An effort to assemble this data would be a valuable contribution to this modeling effort.

5 Summary and Future Work

We have developed a forward model that characterizes the probability that a state will pursue a nuclear weapons progam based on a set of eight socio-political and technical factors: governing structure, reactor technology, inter-state conflict, enrichment technology, military isolation, military spending, scientific network, and indigenous uranium reserves. To develop this model, we first assembled a historical database of quantitative data to characterize the factors, and then used the database to determine the degree to which each factor is correlated to a pursuit decision. Historical data was also used to inform the conversion between the pursuit score and a likelihood of developing a weapons program.

Our analysis yielded unexpected results for two of the eight factors suggested by political science literature as motivations for pursuing weapons. The presence of uranium reserves was uncorrelated to a pursuit decision, suggesting that access to natural uranium is not a bottleneck. Perhaps more surprising, access to reactor technology was anti-correlated with a pursuit decision, meaning the more reactors a state had, the less likely it was to pursue. It is possible that this effect is a consequence of the existing nonproliferation regime - states that make the strongest nonproliferation commitments are rewarded with assistance in developing nuclear energy programs. It would be instructive to investigate both of these factors further, for example, to see whether there is a distinction in the correlation of research versus commercial reactors to a pursuit decision.

It is important to note that this model is meant to be indicative rather than predictive. Human behavior is fundamentally difficult to explain, let alone model. The actions of individuals can have outsized effects, for example A.Q. Khan's role in Pakistan's weapons program. Humans do not always act rationally, and groups can make very different decisions from individuals. Expertise from psychology, game theory, sociology and international relations could certainly improve our model. Ultimately though,there will always be some level of unpredictability in human behavior that prevents models such as this from being predictive.

Nonetheless, we believe this model can be used to offer valuable insights into the relative risks of potential future nonproliferation paradigms. While we cannot predict whether or not State A will pursue a weapon in the next 10 years, we can investigate ways to reduce the risk of that pursuit occurring based on our understanding of these factors. For example, we are currently applying the model to scenarios considering the creation of regional multilateral enrichment facilities as a means of reducing the spread of enrichment technology. Would a regional multilateral enrichment agreement in the Middle East reduce proliferation risk under all possible conflict scenarios, or are there potential landscapes in which risk would not be further mitigated by such an approach? We anticipate that the model will also be useful in examining the impacts of other future proposed treaties or international agreements.

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