Emergence & Convergence

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Emergence & Convergence

- **Multi-year study** on the impact of emerging technologies on the WMD space
  - Threat space – Risks and Opportunities
  - Governance space – Impact on existing tools, need for new approaches
- **Subject matter expert survey** to assess risks and opportunities
  - Five technology groups – additive manufacturing, advanced robotics, nanotechnology, nuclear technology, and synthetic biology
  - Launched on 30 June 2016 and remained open until 31 December 2016
  - Survey invitation sent to about 3,500 SMEs across DoD, the interagency, academia, industry, think-tanks, etc.
  - 176 SMEs agreed to complete the survey
  - We received 120 completed surveys with a response rate of 68%

Emergence & Convergence

- **What is an emerging technology?**
  - Emerging technologies are best understood as science-based innovations with the potential to create a new industry or transform an existing one
  - Emerging technologies demonstrate a number features that help to distinguish them from other technologies, most significantly their **disruptiveness** and **convergence**
  - Many emerging technologies are disruptive; they are cheaper, simpler, smaller and often more convenient to use
- **What is convergence?**
  - Convergence refers to the synergistic integration of new technologies, each of which is progressing at a rapid rate and interacting with more established fields.

Emerging Technologies

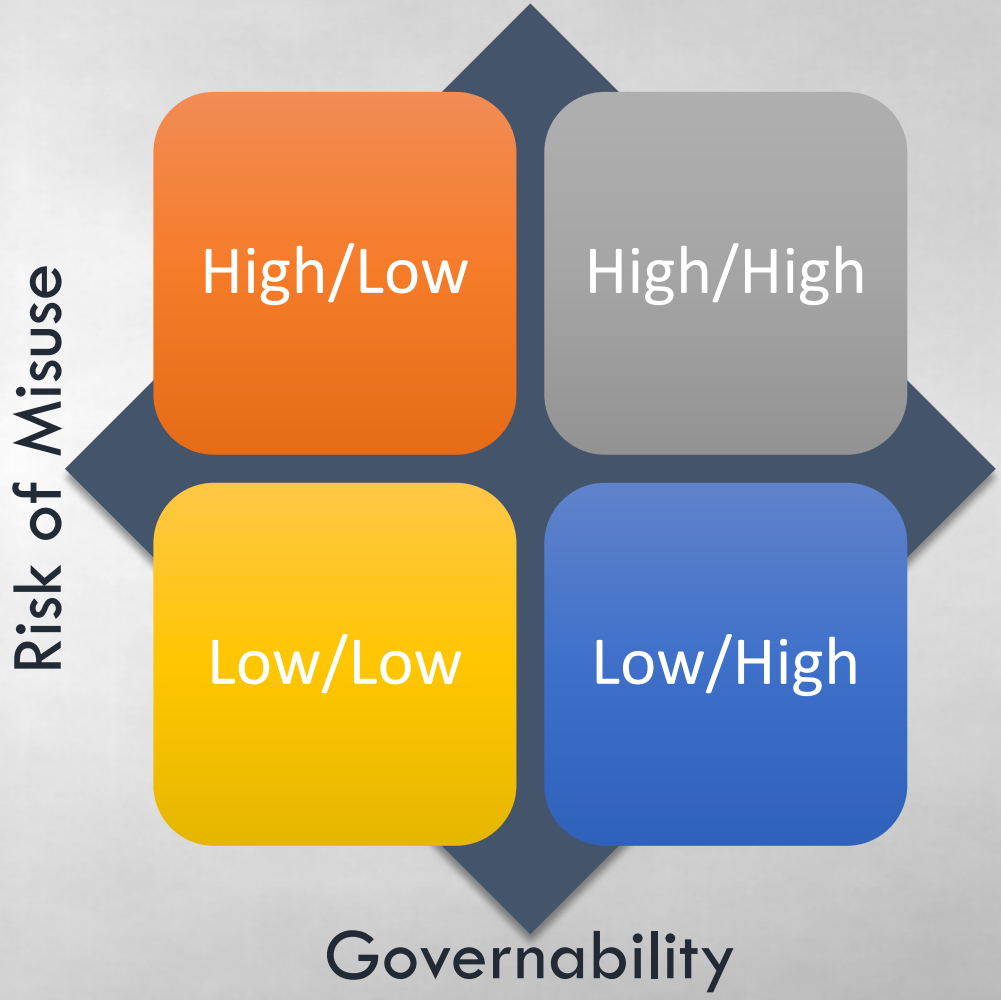
- **Additive Manufacturing**
  - The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods
  - Additive manufacturing is used to build physical models, prototypes, patterns, tooling components, and production parts
- **Advanced Robotics**
  - A branch of mechanical engineering, electrical engineering, electronics engineering and computer science that focuses on the development of robotics and artificial intelligence
  - A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed functions for the performance of a variety of tasks

Emerging Technologies

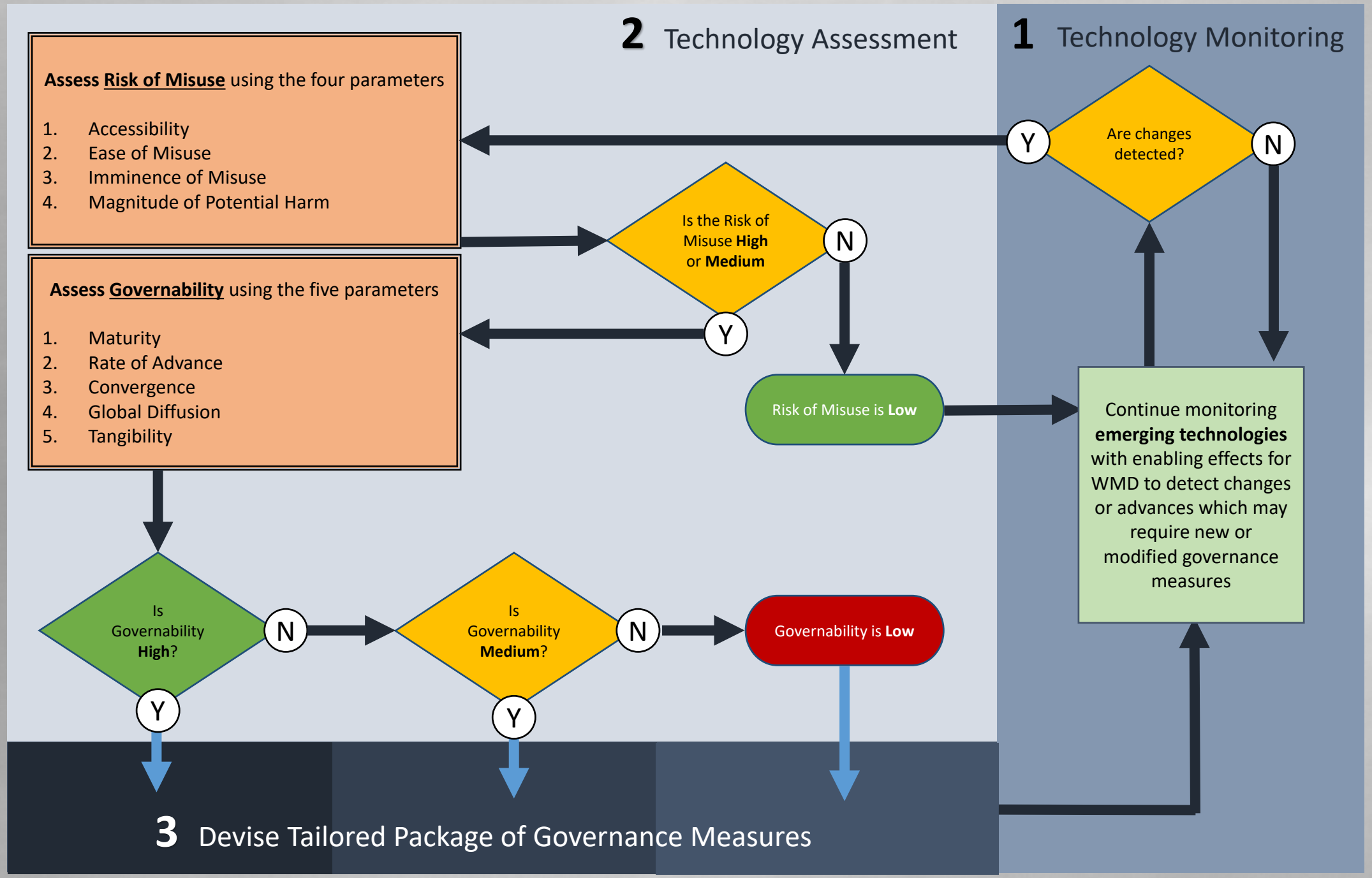
- **Nanotechnology**
  - Applied science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers. Nanotechnology refers to a group of technologies which manipulate and control nanoscale materials to exploit special properties (quantum effects) and produce new applications
- **Nuclear Technology**
  - New ways to exploit the atom to generate electricity (such as nuclear fusion), new types of nuclear reactors, or new ways for producing fissile material
- **Synthetic Biology**
  - The convergence of advances in chemistry, biology, computer science, and engineering that enables us to go from idea to product faster, cheaper, and with greater precision than ever before
  - It can be thought of as a biology-based “toolkit” that uses abstraction, standardization, and automated construction to change how we build biological systems and expand the range of possible products

Risk Assessment Framework

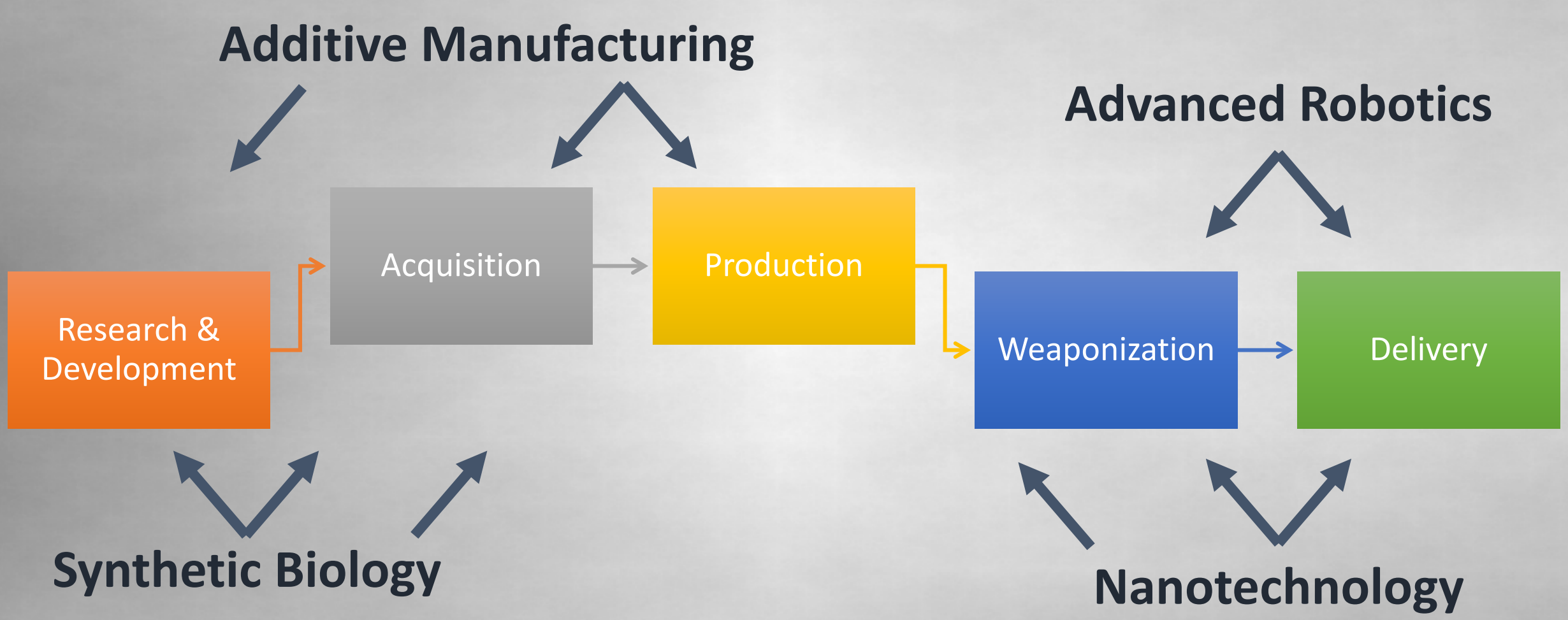
- **Risk of Misuse**
  - Accessibility
  - Ease of Misuse
  - Imminence of Misuse
  - Magnitude of Potential Harm
- **Governability**
  - Maturity
  - Rate of Advance
  - Convergence
  - Global Diffusion
  - Tangibility



Decision Framework

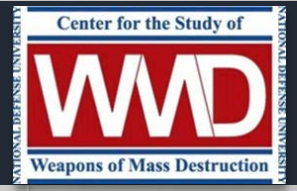


WMD Development Pathways

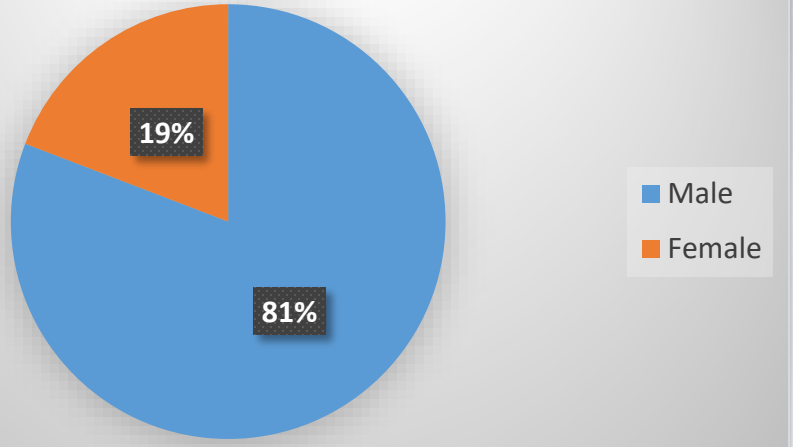


The Respondents

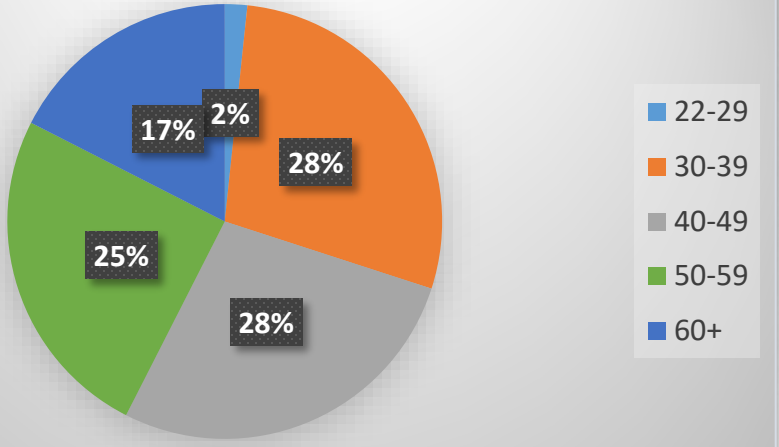
Survey Population



Gender Distribution

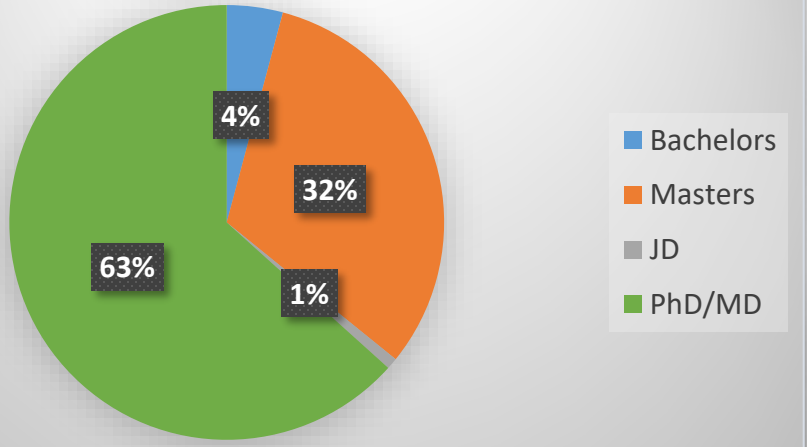


Age Distribution



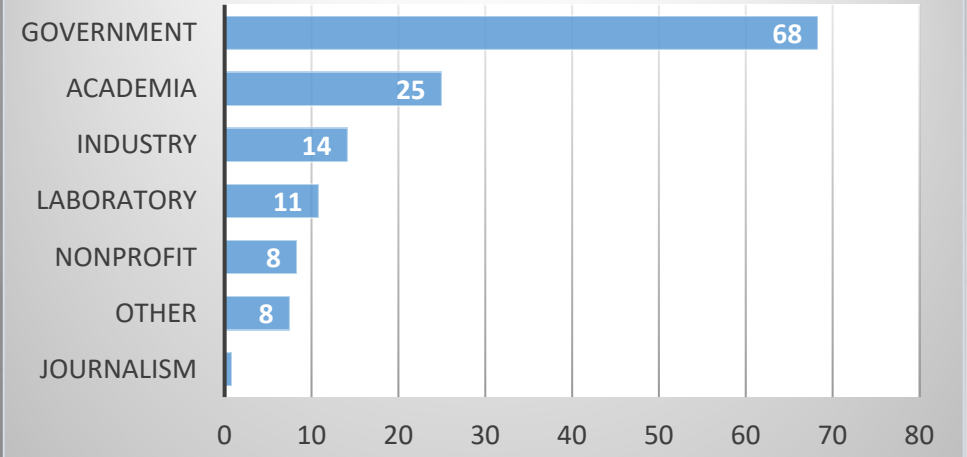
120 Responses

Education

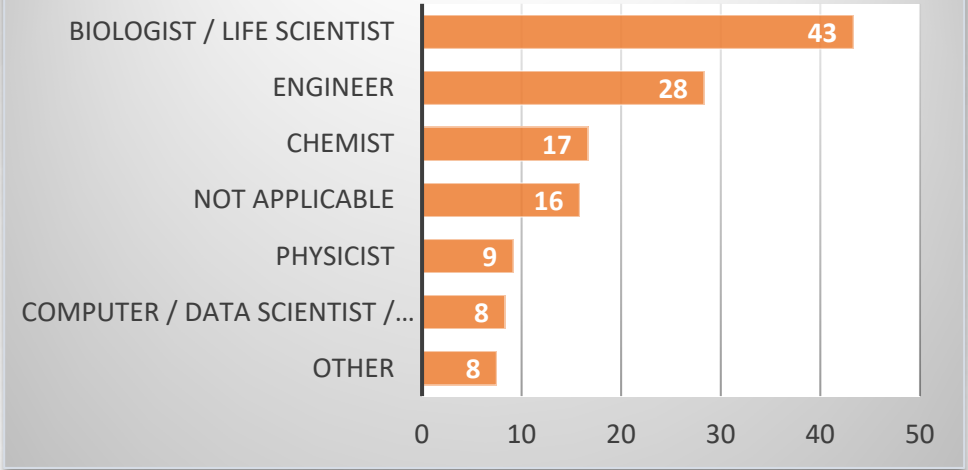


Survey Population

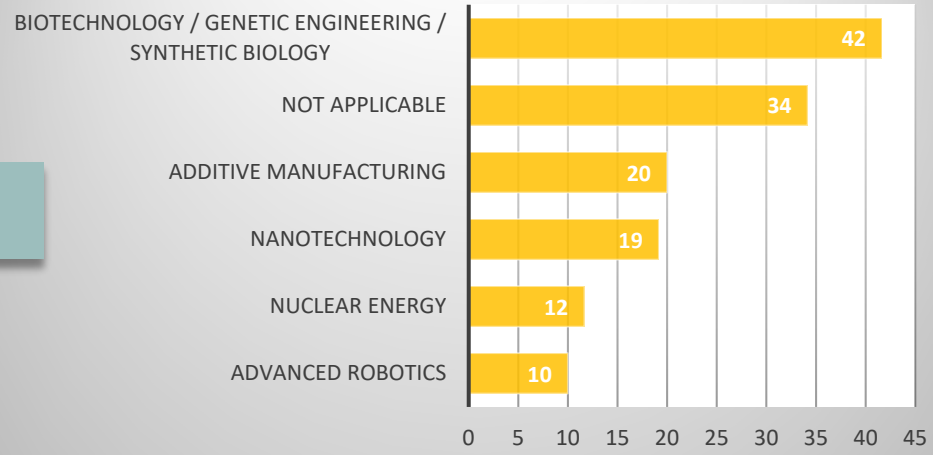
Sector



Scientific / Technical Discipline

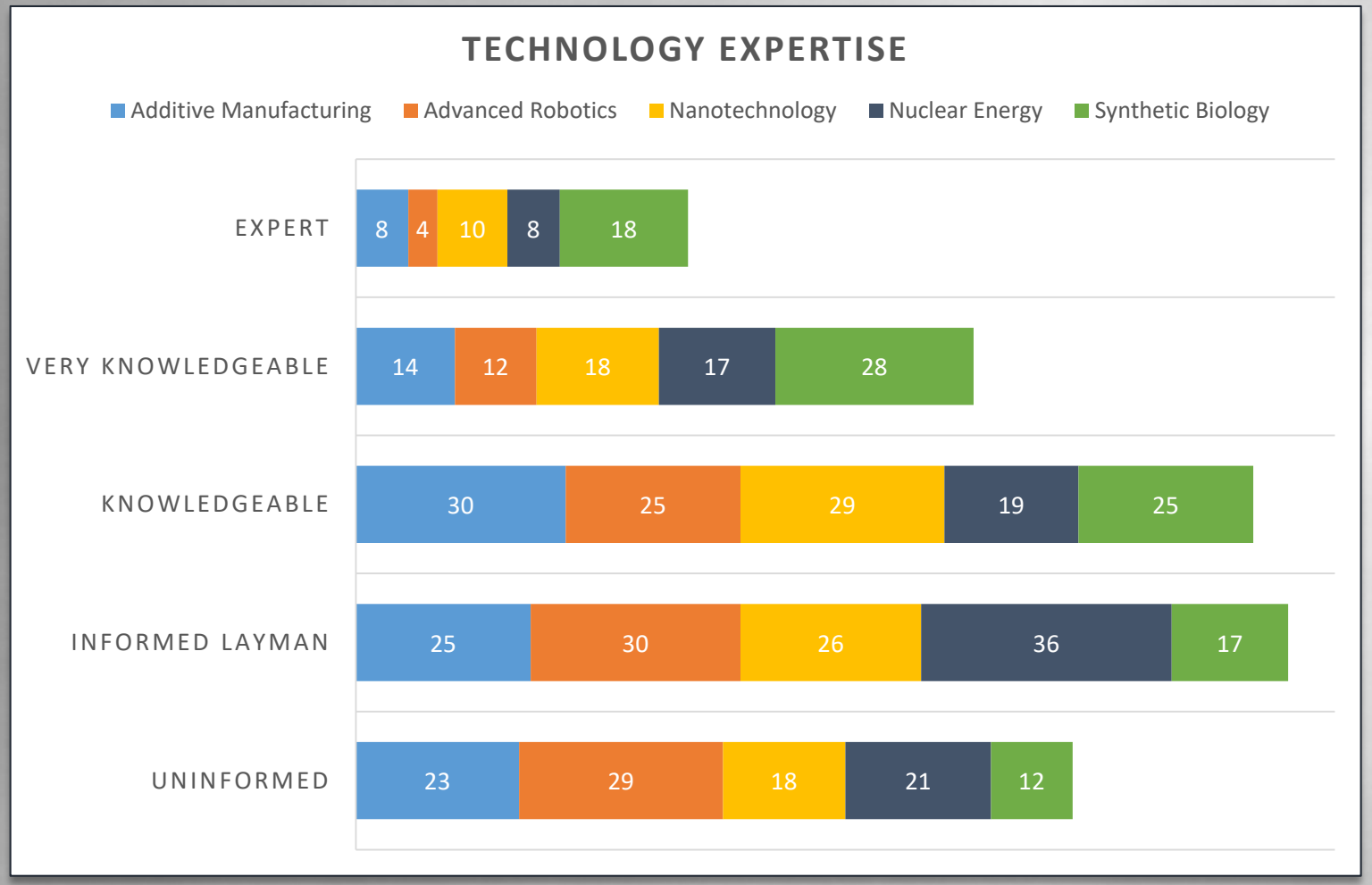


Emerging Tech Experience



120 Responses

Survey Population



120 Responses

Risk of Misuse & Governability

The Parameters

Risk of Misuse

Risk of Misuse	Accessibility	Ease of Misuse	Imminence	Magnitude
Low	Low	Low	Low	Low
Medium	Medium	Medium	Medium	Medium
High	High	High	High	High

Governability

Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Low	Low	High	High	High	Low
Medium	High	Medium	Medium	Medium	Medium
High	Medium	Low	Low	Low	High

Risk of Misuse & Governability

Center for the Study of WMD — Weapons of Mass Destruction

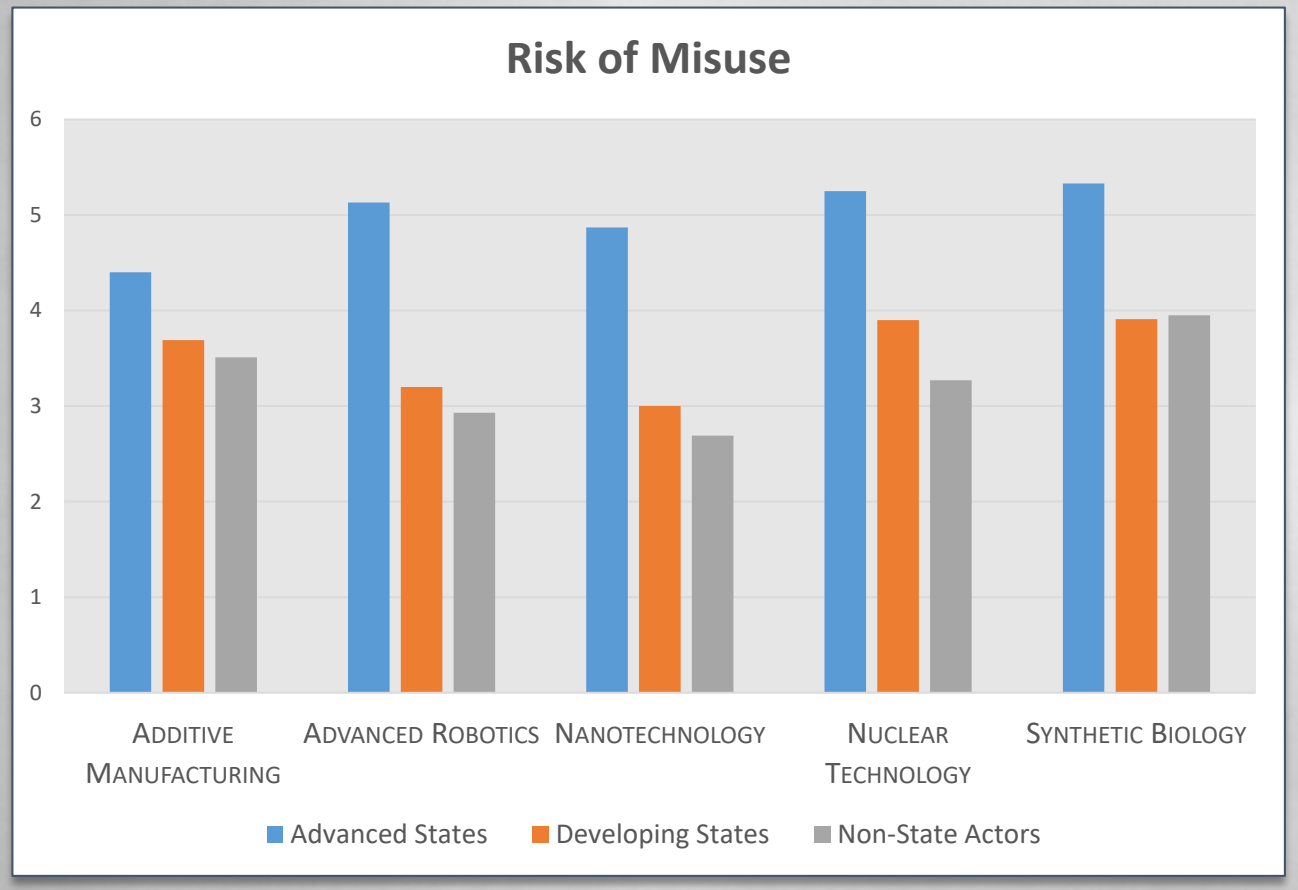
	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Additive Manufacturing											
Advanced States	4.40	6.65	5.68	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Developing States	3.69	5.03	4.41	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Non-State Actors	3.51	4.52	4.03	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Advanced Robotics											
Advanced States	5.13	6.32	5.36	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Developing States	3.20	3.96	3.85	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Non-State Actors	2.93	3.27	3.27	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Nanotechnology											
Advanced States	4.87	6.16	5.03	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Developing States	3.00	3.61	3.17	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Non-State Actors	2.69	2.85	2.65	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Nuclear Technology											
Advanced States	5.25	5.83	5.07	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Developing States	3.90	3.33	3.45	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Non-State Actors	3.27	2.49	2.75	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Synthetic Biology											
Advanced States	5.33	6.35	5.56	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85
Developing States	3.91	4.67	4.14	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85
Non-State Actors	3.95	4.21	3.77	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85

Average Score	Color*
1.0 – 1.49	
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

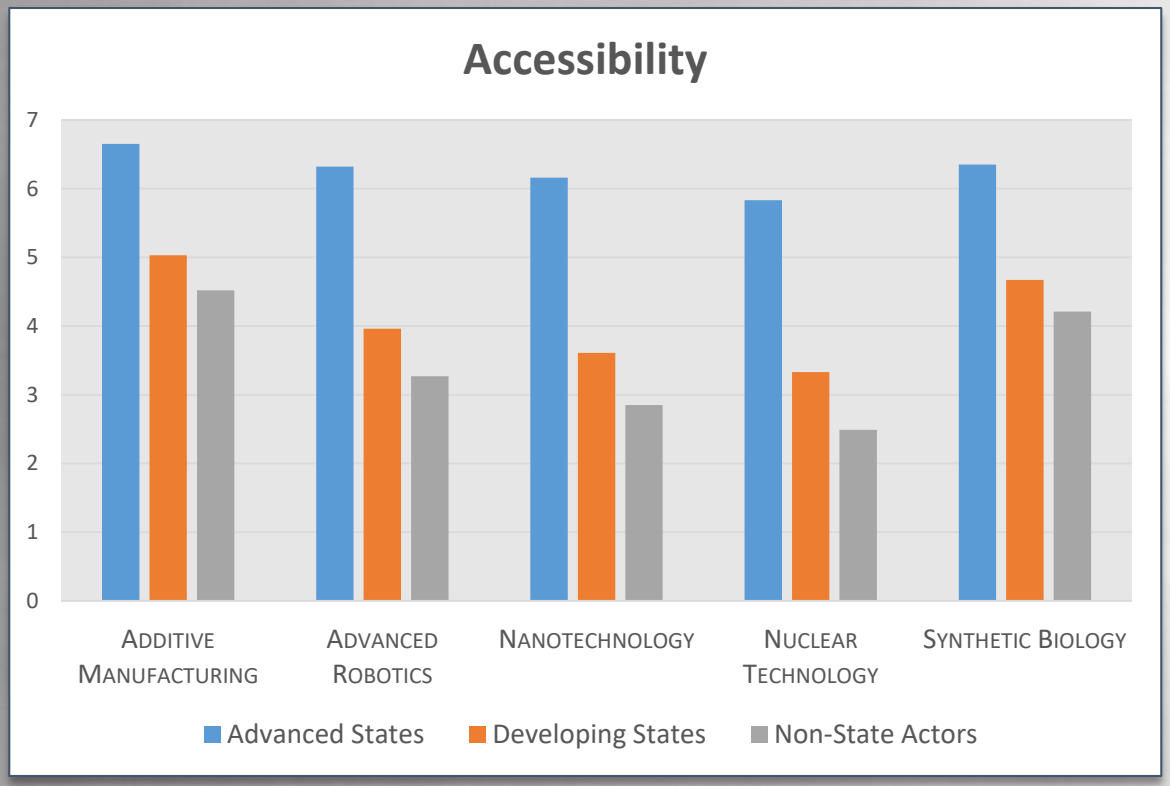
*Colors are flipped for the **tangibility** and **governability** parameters

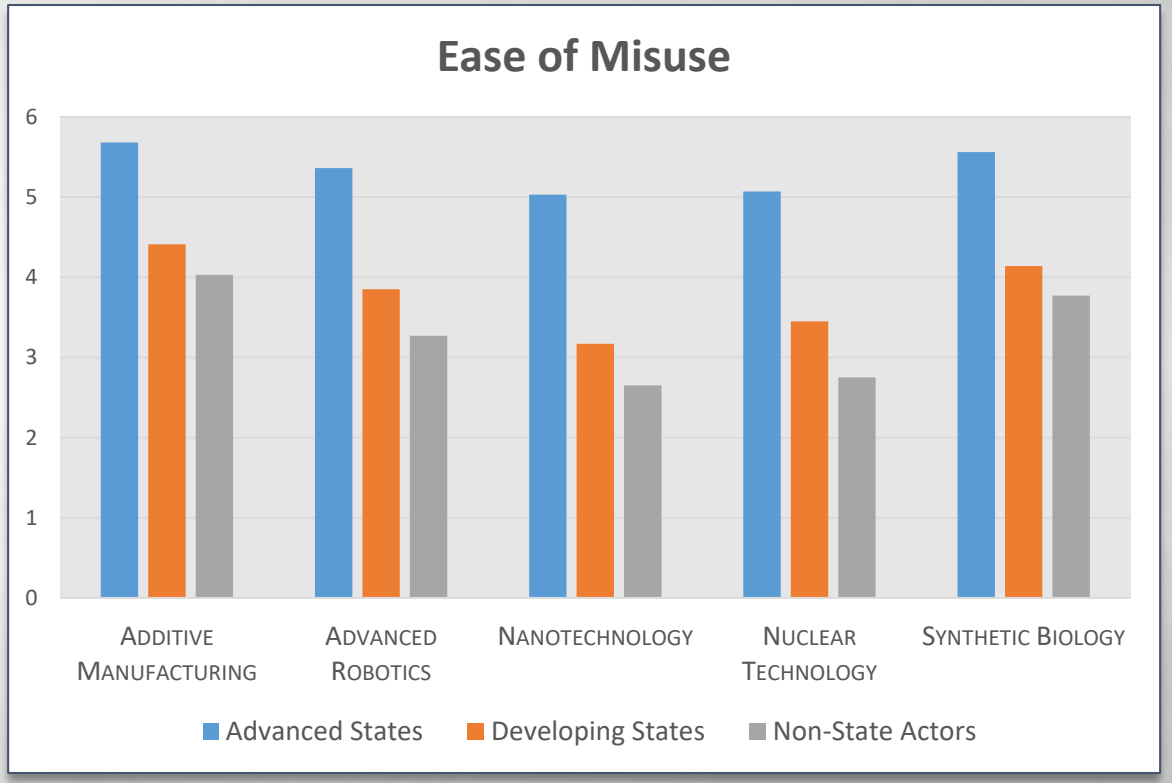
Colors are adjusted slightly for the **maturity parameter

Risk of Misuse



Risk of Misuse





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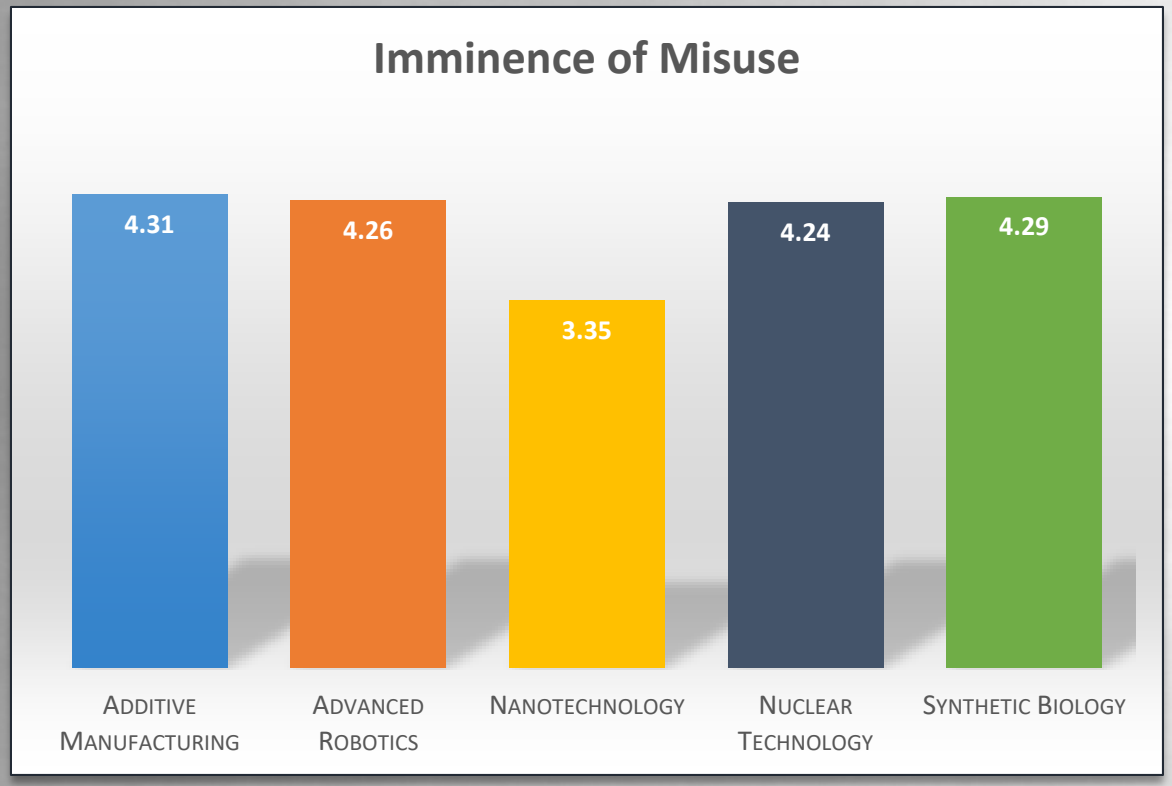
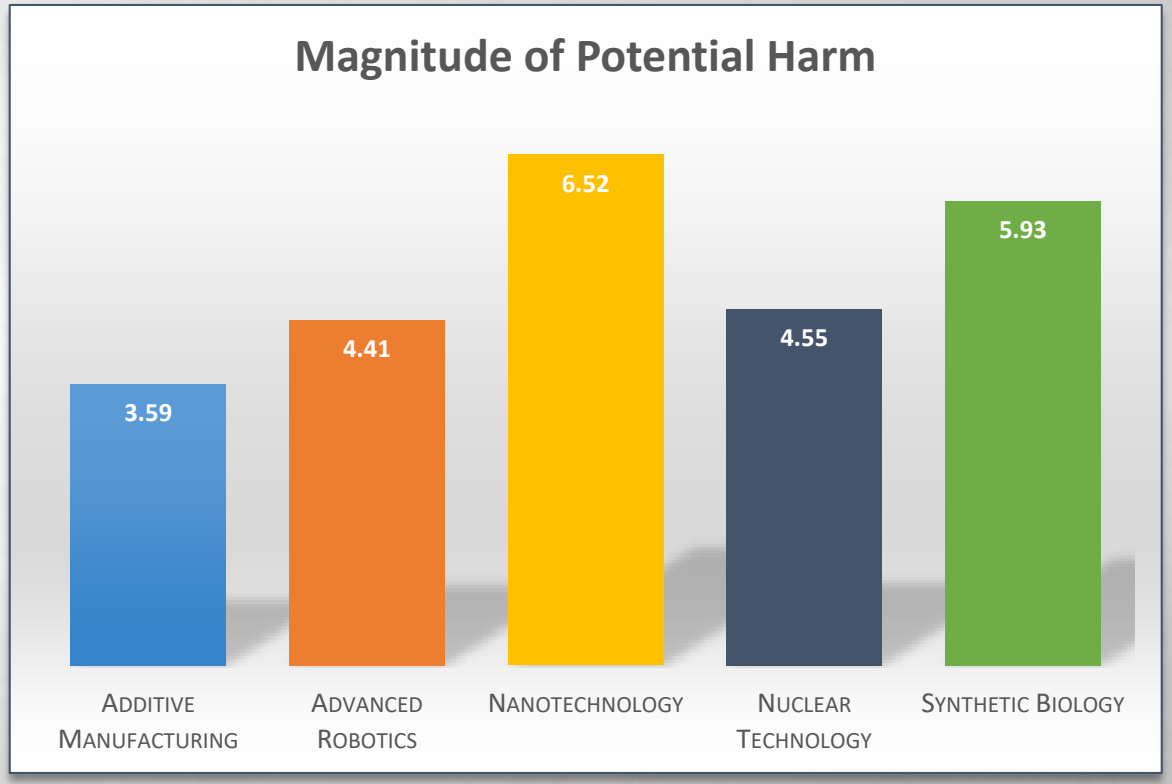
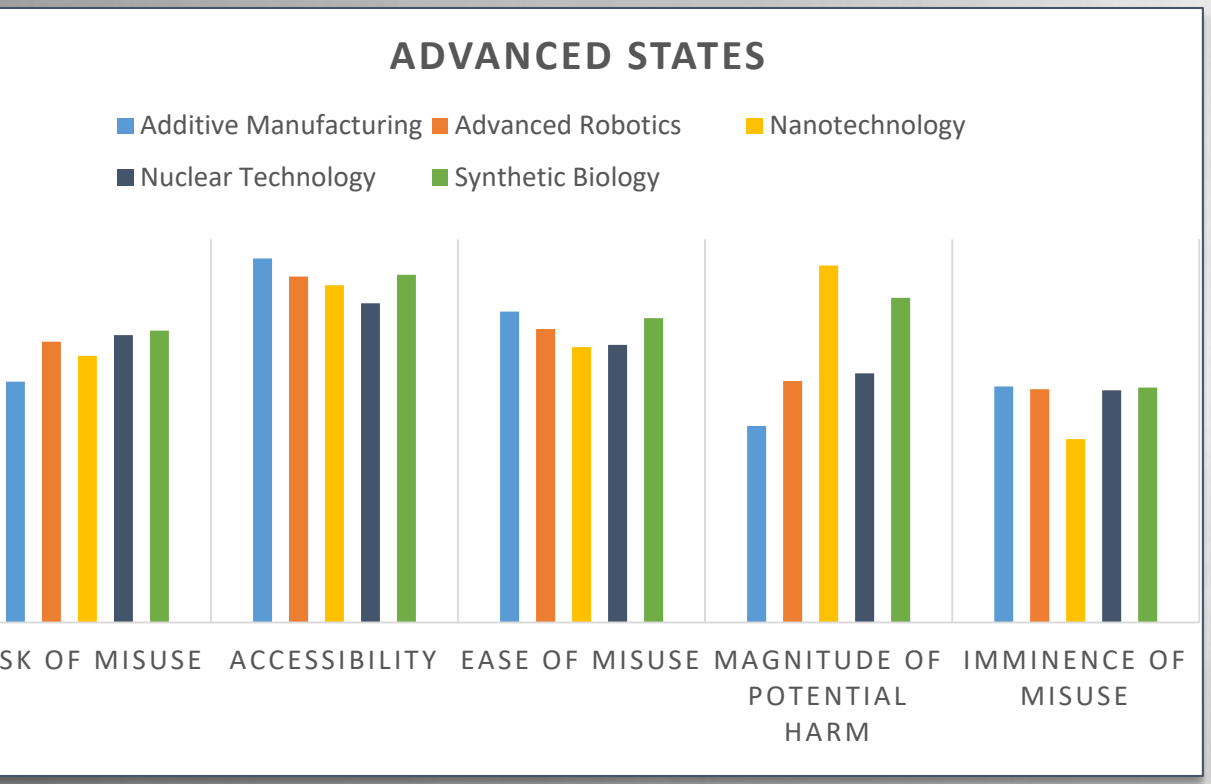
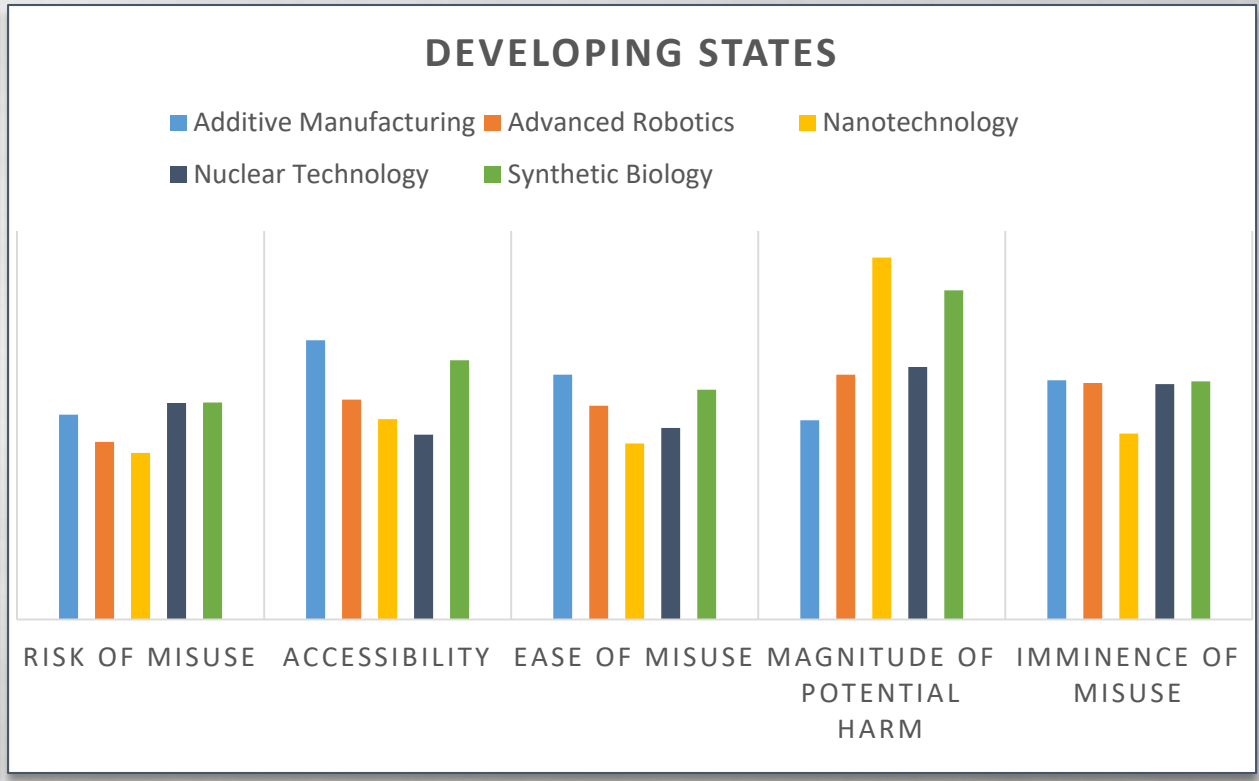


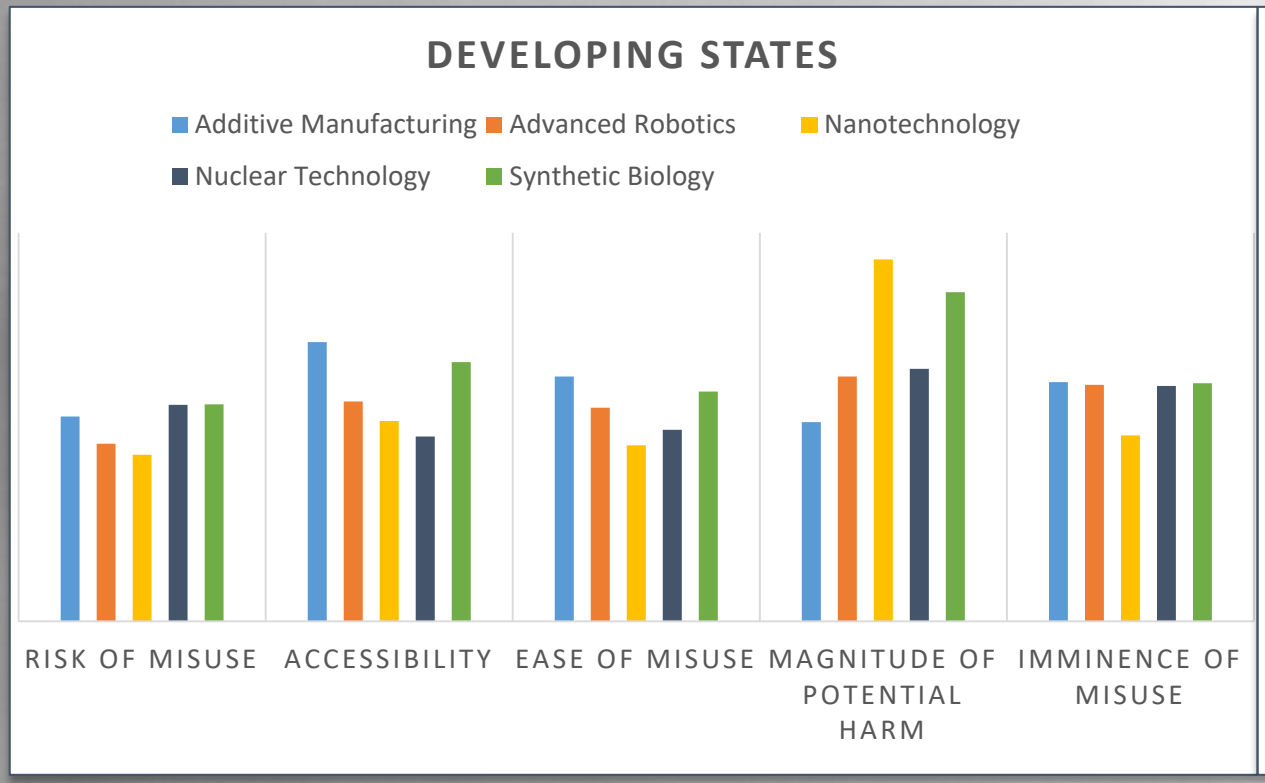


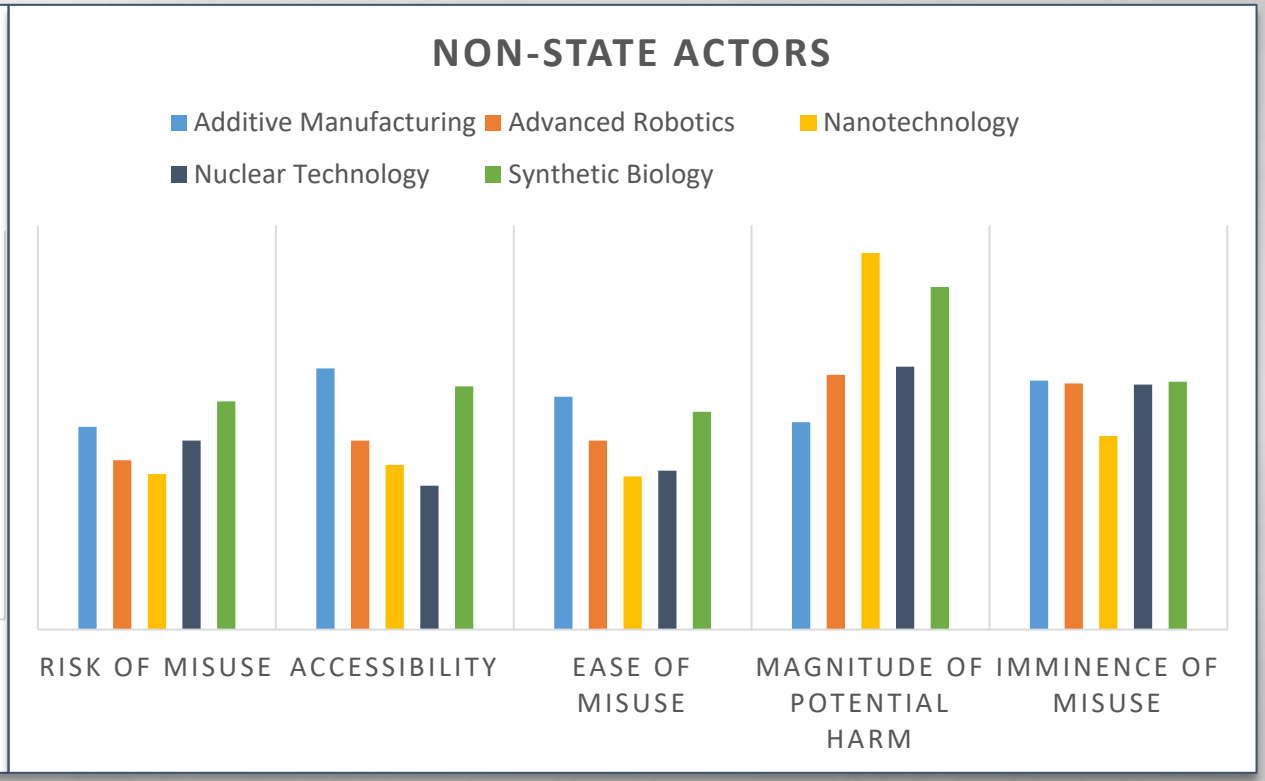
Advanced vs. Developing States



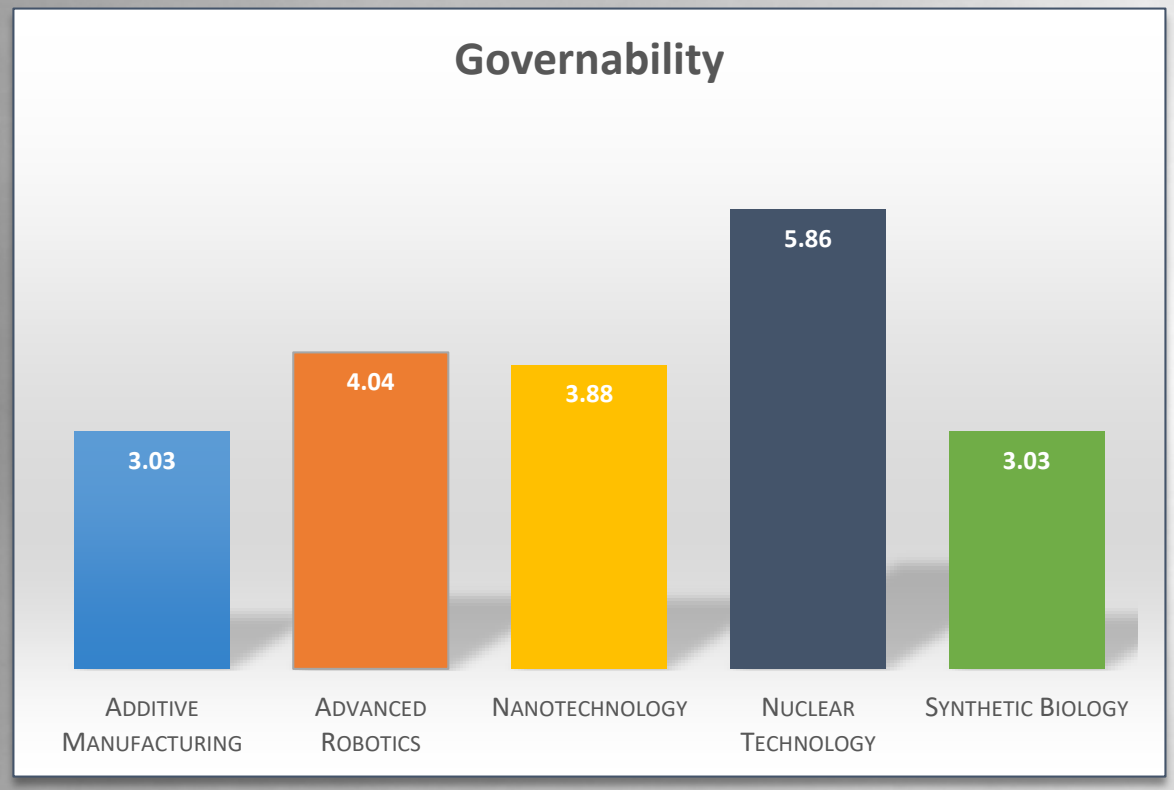


Developing States vs. Non-state Actors





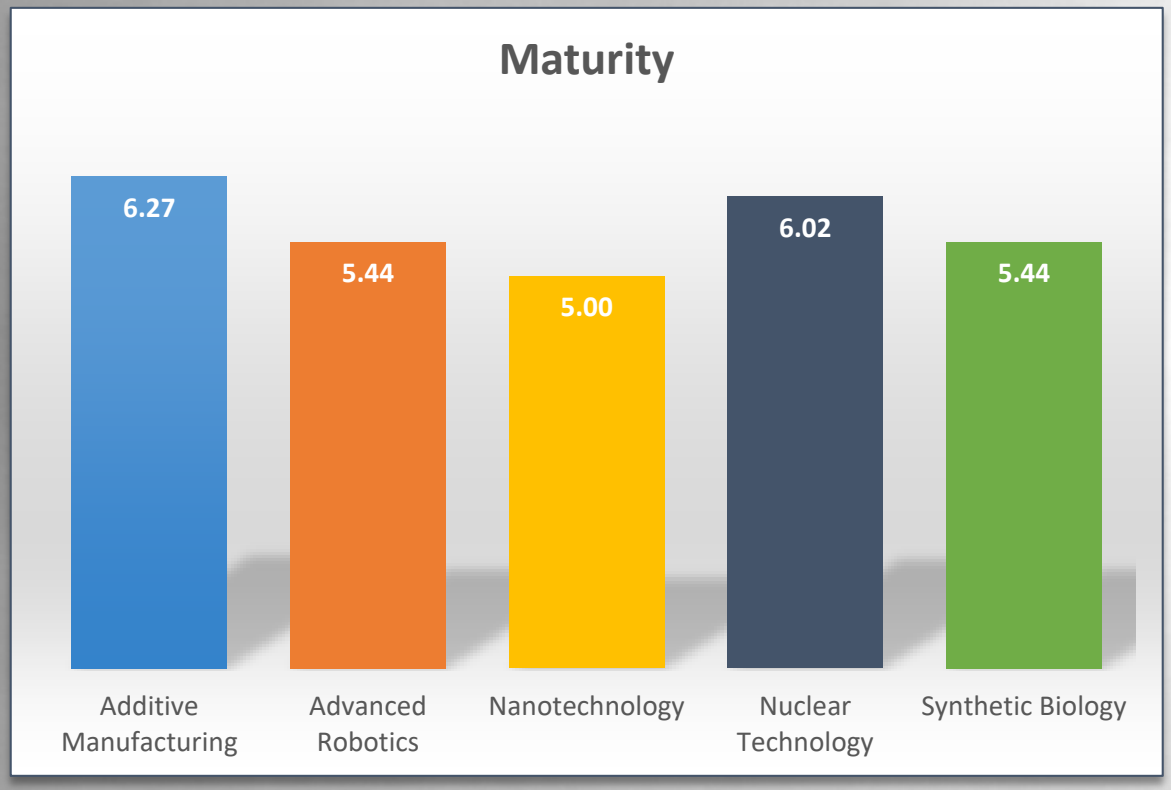
Governability

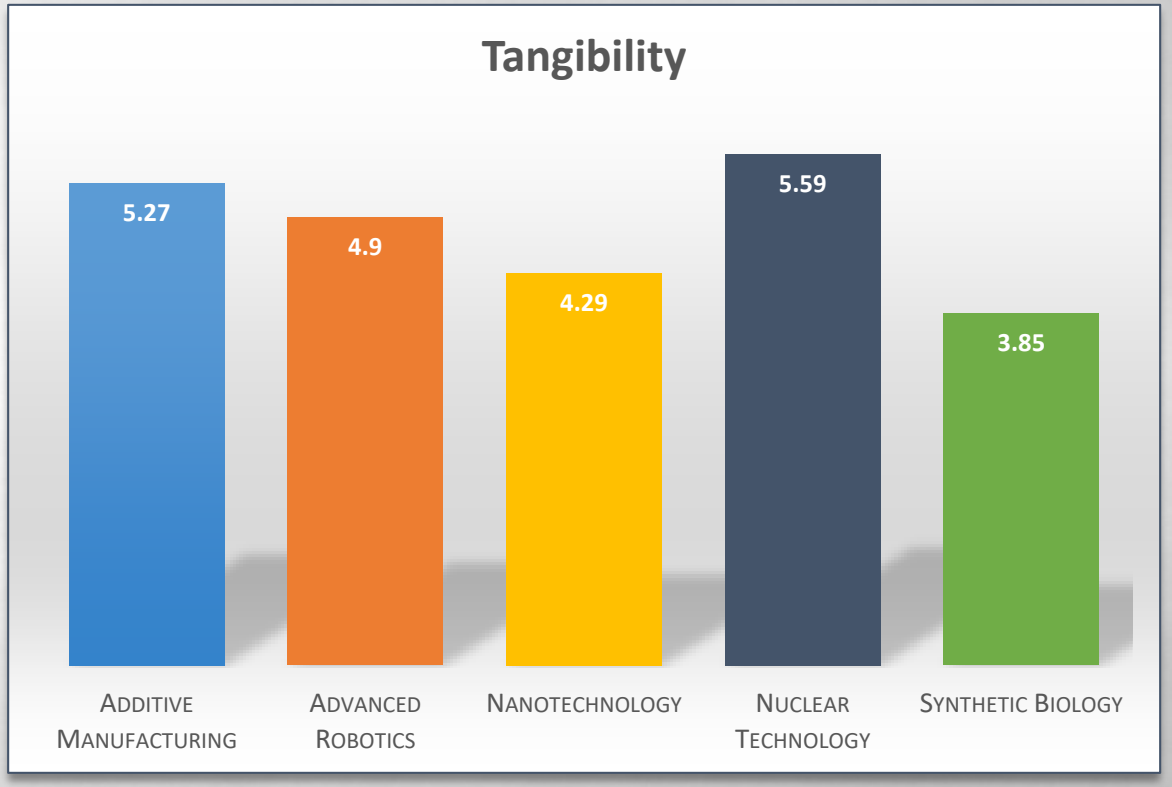


Governability is based on five parameters:

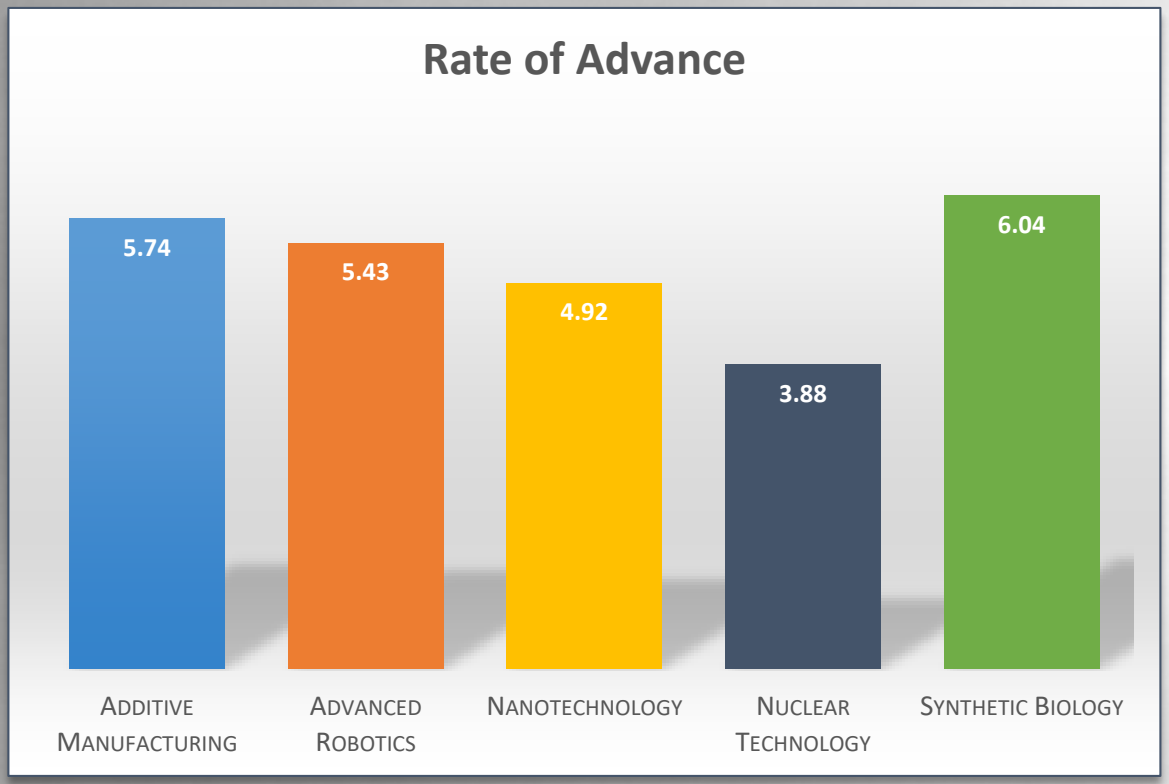
- Maturity
- Rate of Advance
- Convergence
- Global Diffusion
- Tangibility

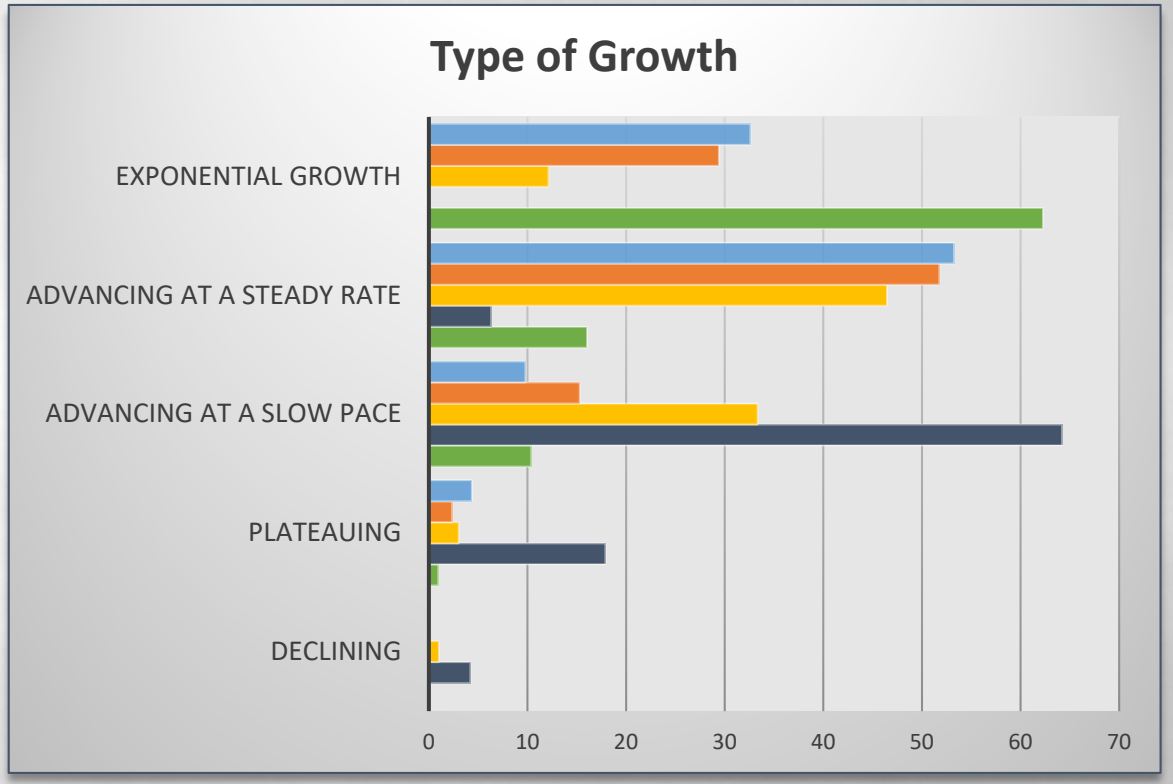
Governability



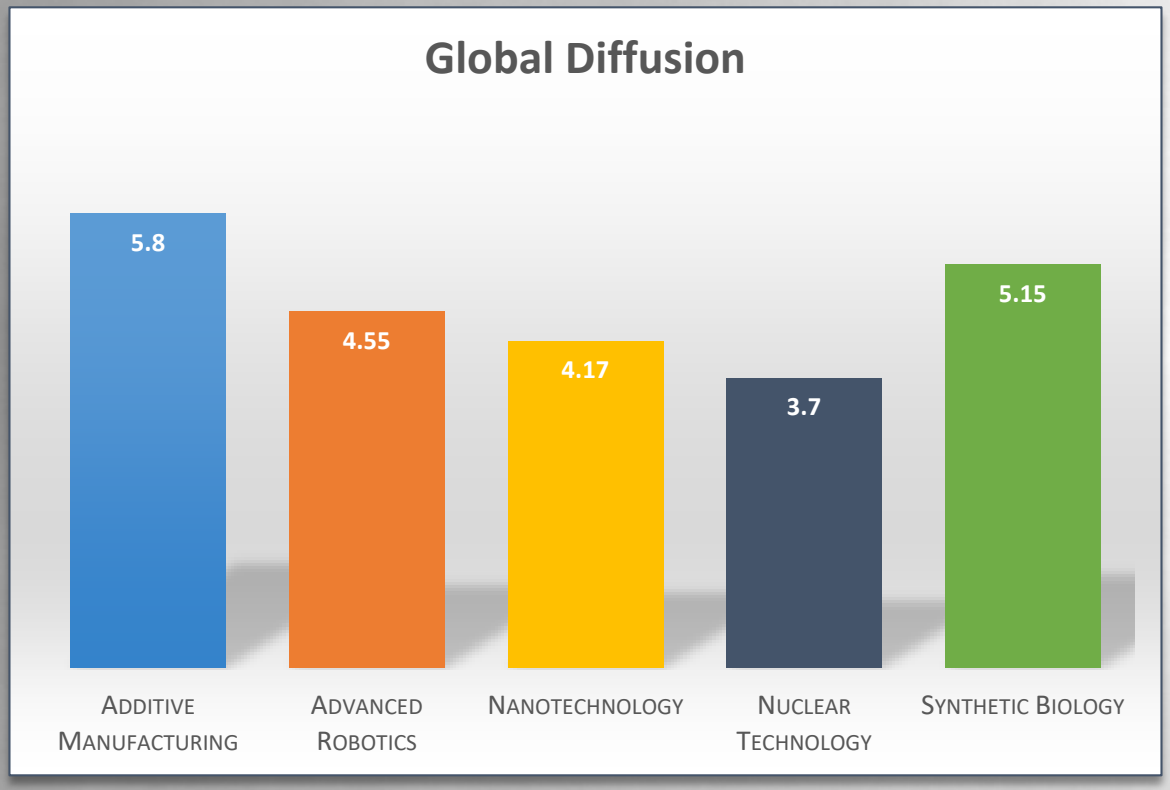


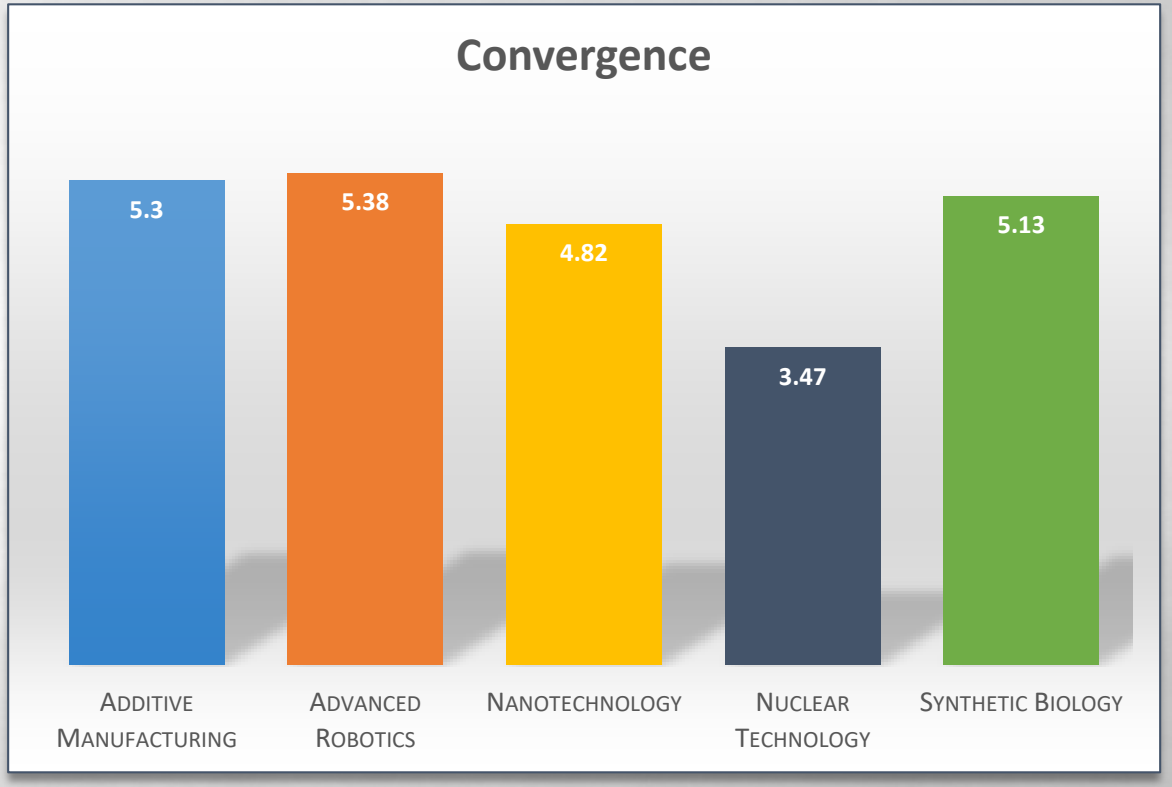
Governability



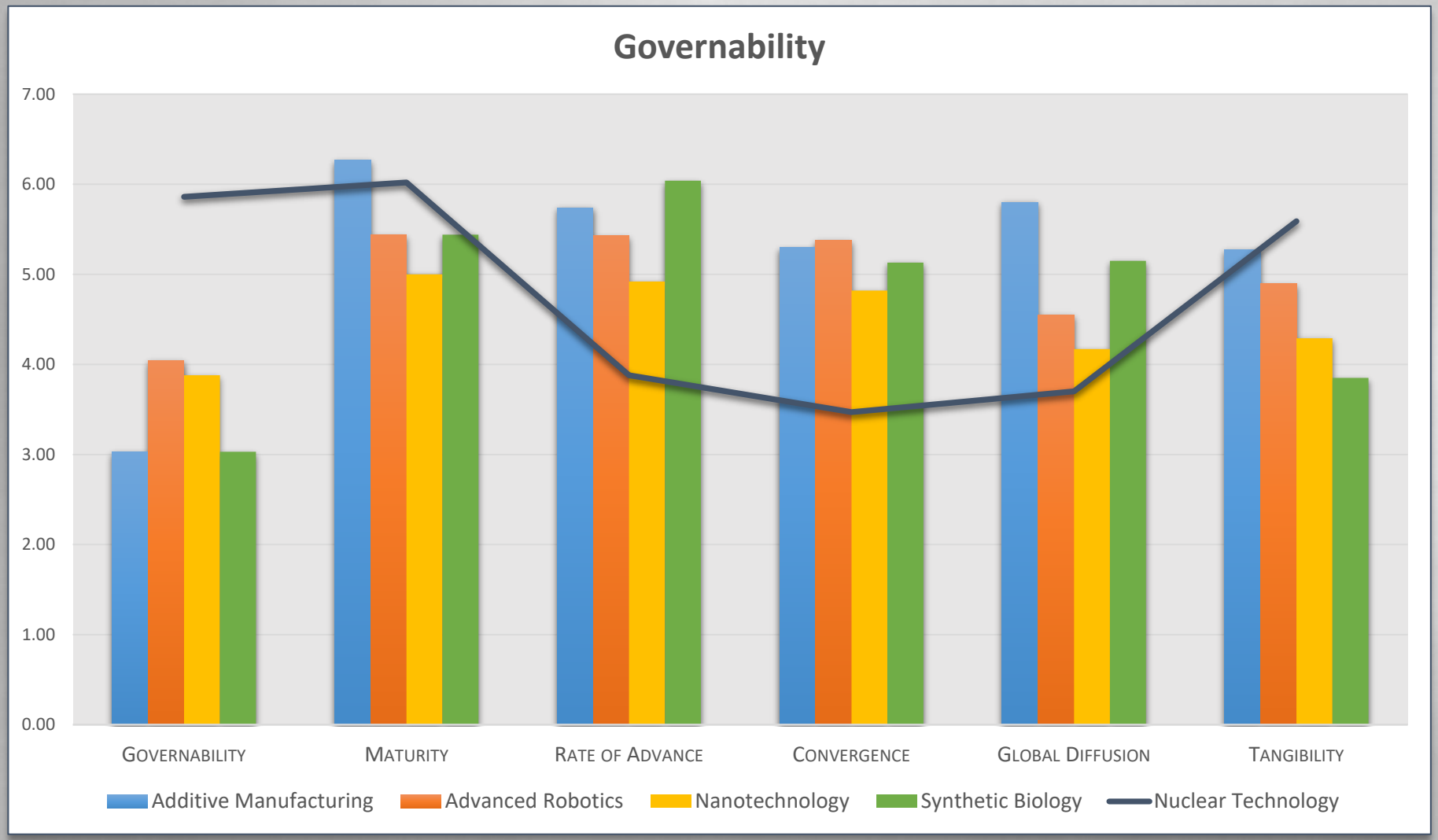


Governability

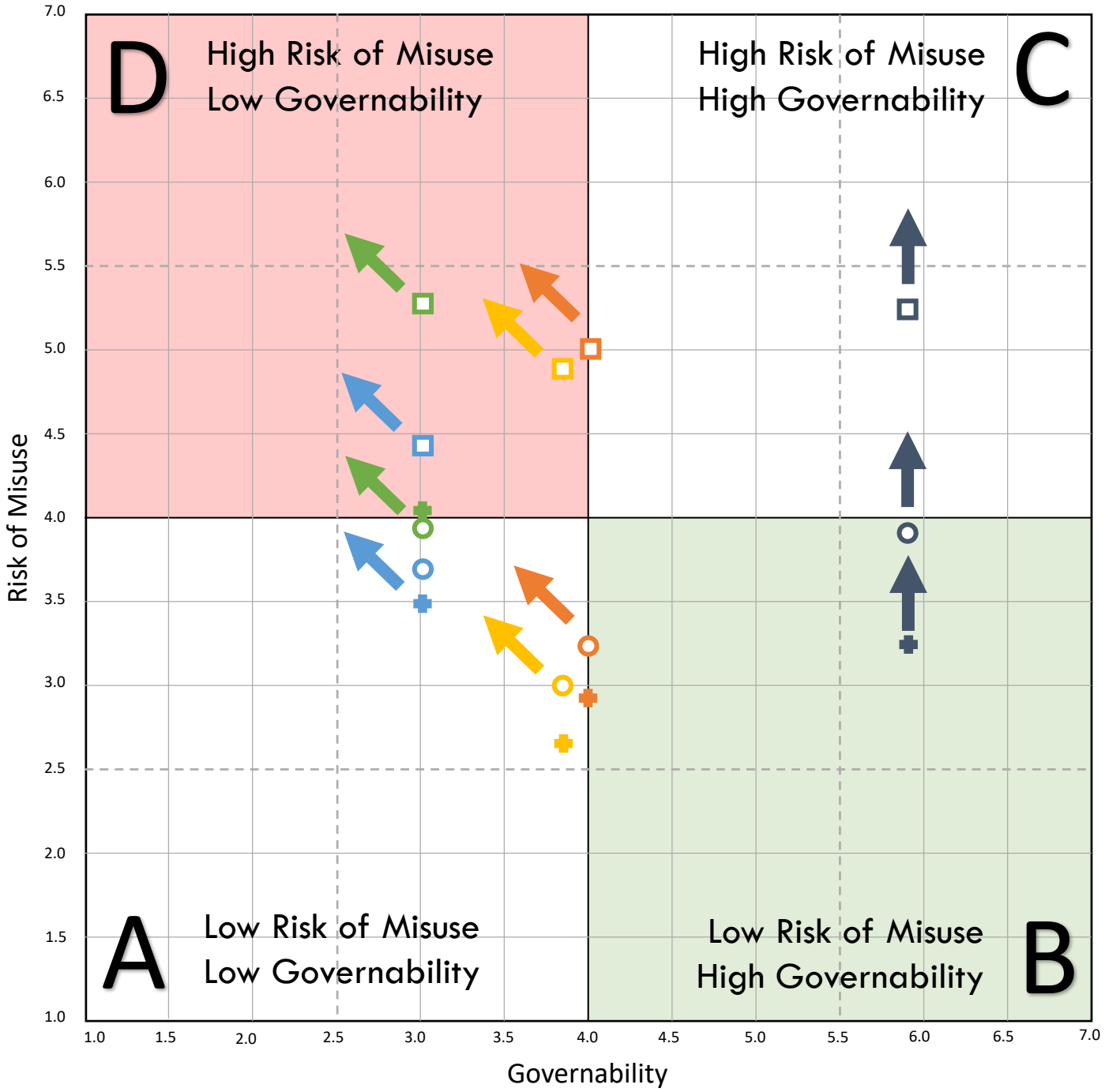




Governability



Risk Assessment Matrix



- Advanced States
- Developing States
- Nonstate Actors

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Additive Manufacturing (AM)

Opportunities - AM

Detection

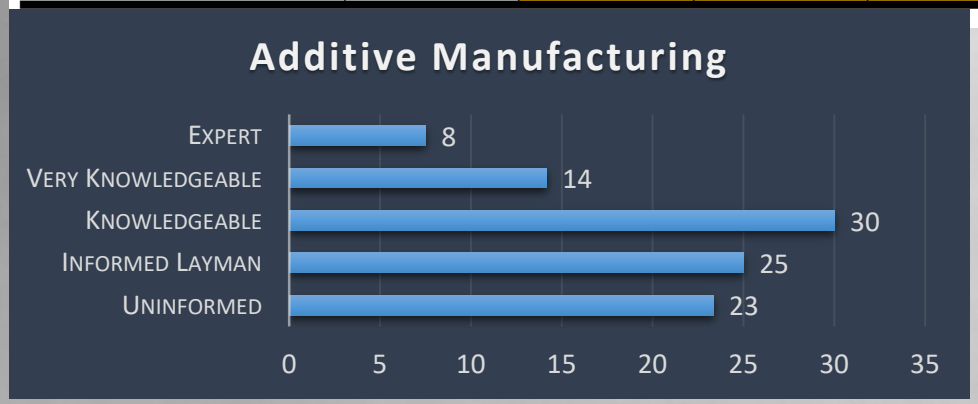
- Rapid prototyping and fabrication of sample collection and sensor components and new detection technology
- Manufacturing of portable, clip-on sensors

Countermeasures

- Local and on-demand manufacturing with a small footprint for needed military parts
- Using printed cell and organ systems for drug testing and medical countermeasures (bioprinting)
- More efficient and cost-effective production of low-volume defense systems

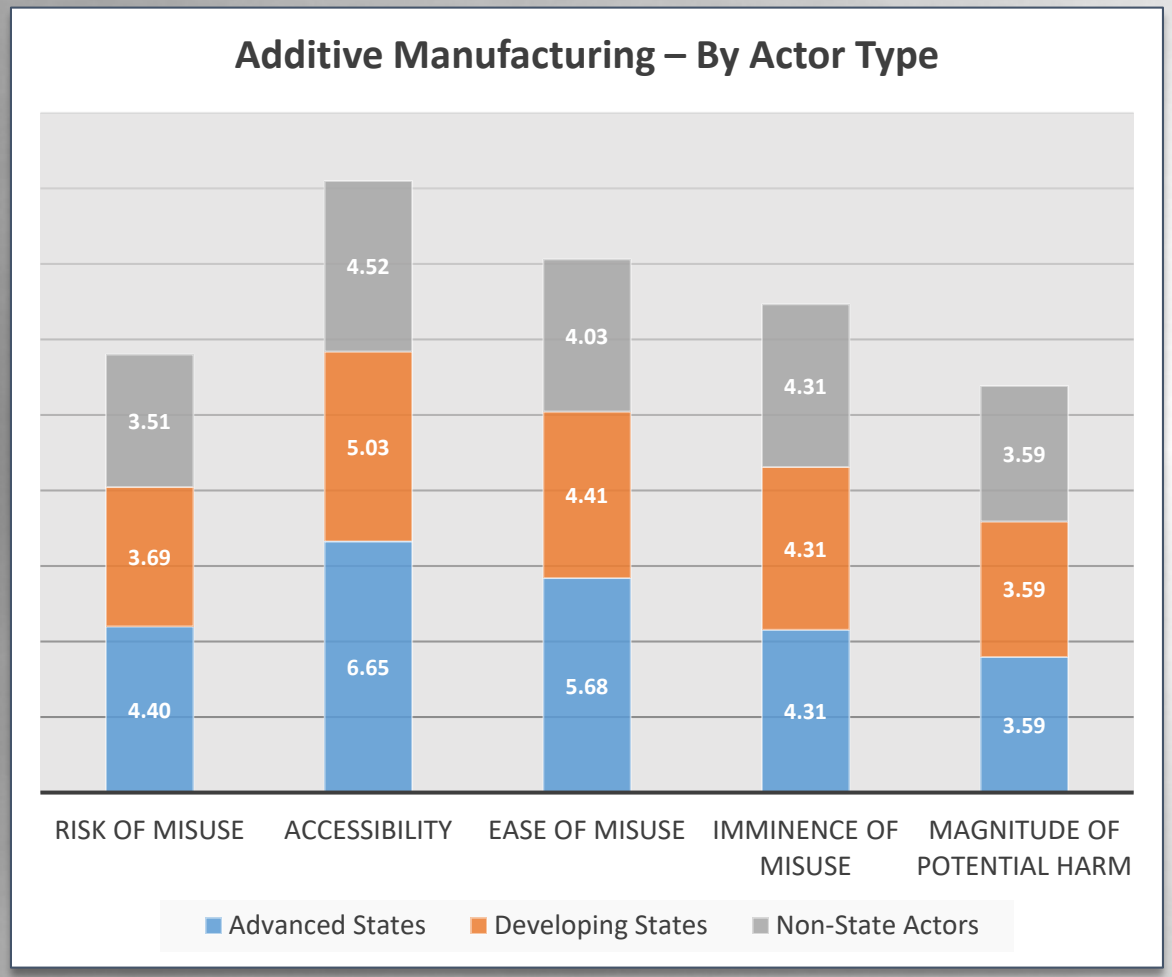
Heat Map - AM

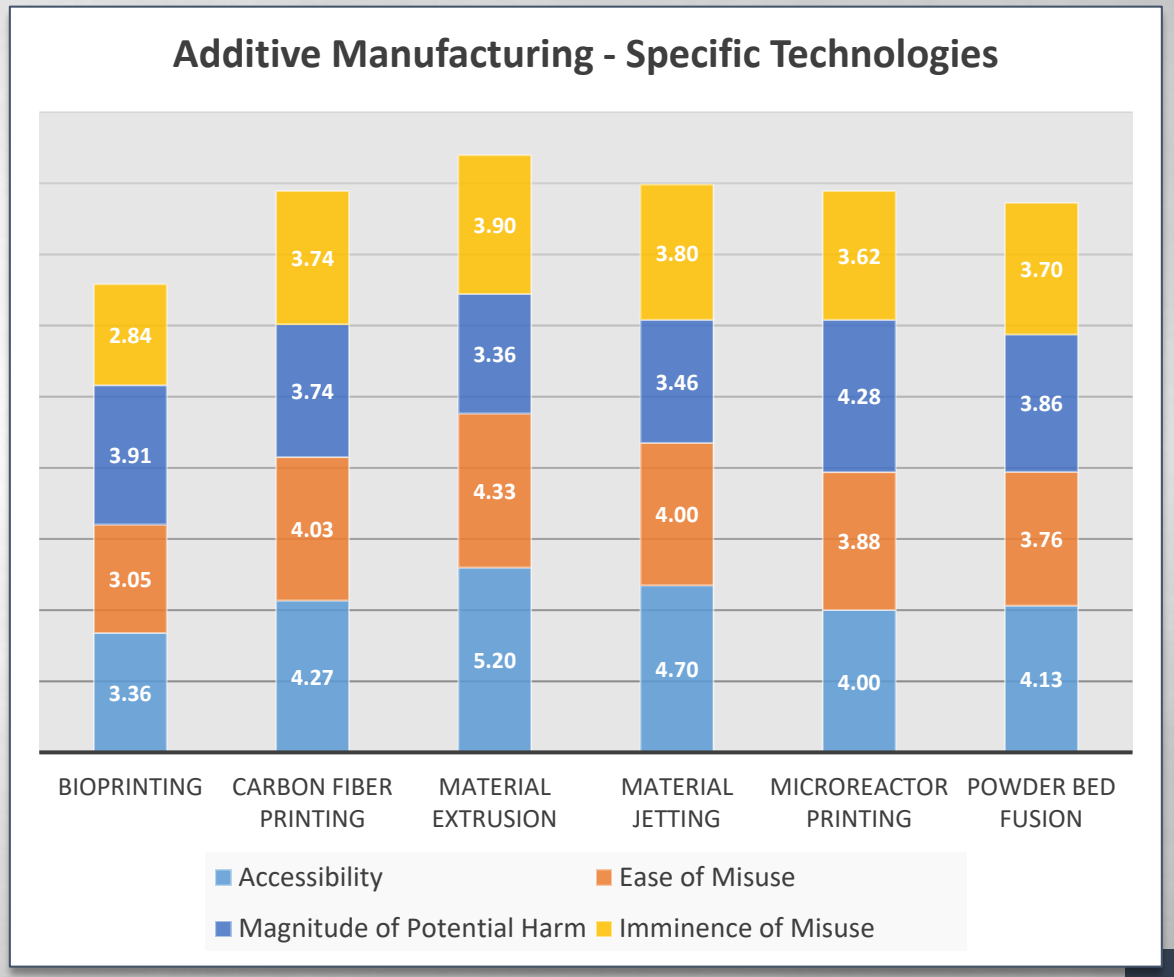
	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Additive Manufacturing											
Advanced States	4.40	6.65	5.68	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Developing States	3.69	5.03	4.41	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Non-State Actors	3.51	4.52	4.03	4.31	3.59	3.03	6.27	5.74	5.30	5.80	5.27
Bioprinting		3.36	3.05	2.84	3.91		3.82				
Carbon Fiber Printing		4.27	4.03	3.74	3.74		5.13				
Material Extrusion		5.20	4.33	3.90	3.36		6.19				
Material Jetting		4.70	4.00	3.80	3.46		5.95				
Microreactor Printing		4.00	3.88	3.62	4.28		4.39				
Powder Bed Fusion		4.13	3.76	3.70	3.86		5.32				



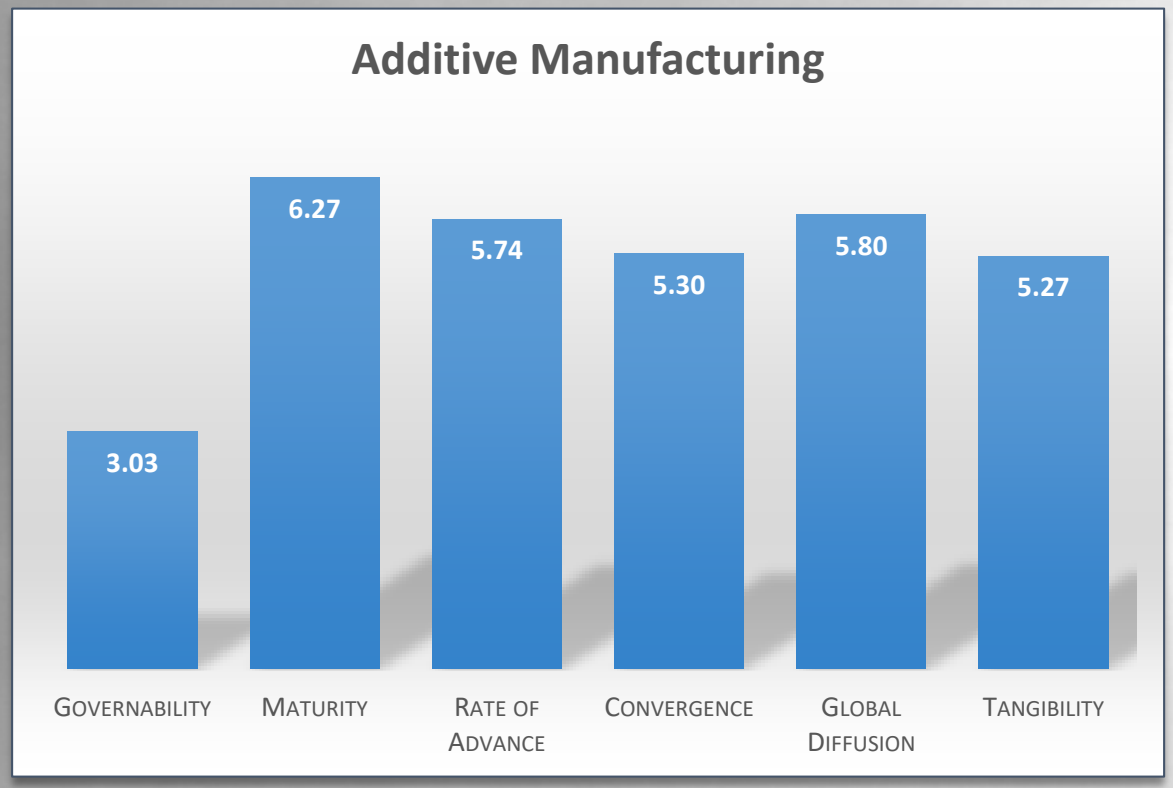
Average Score	Color*
1.0 – 1.49	
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

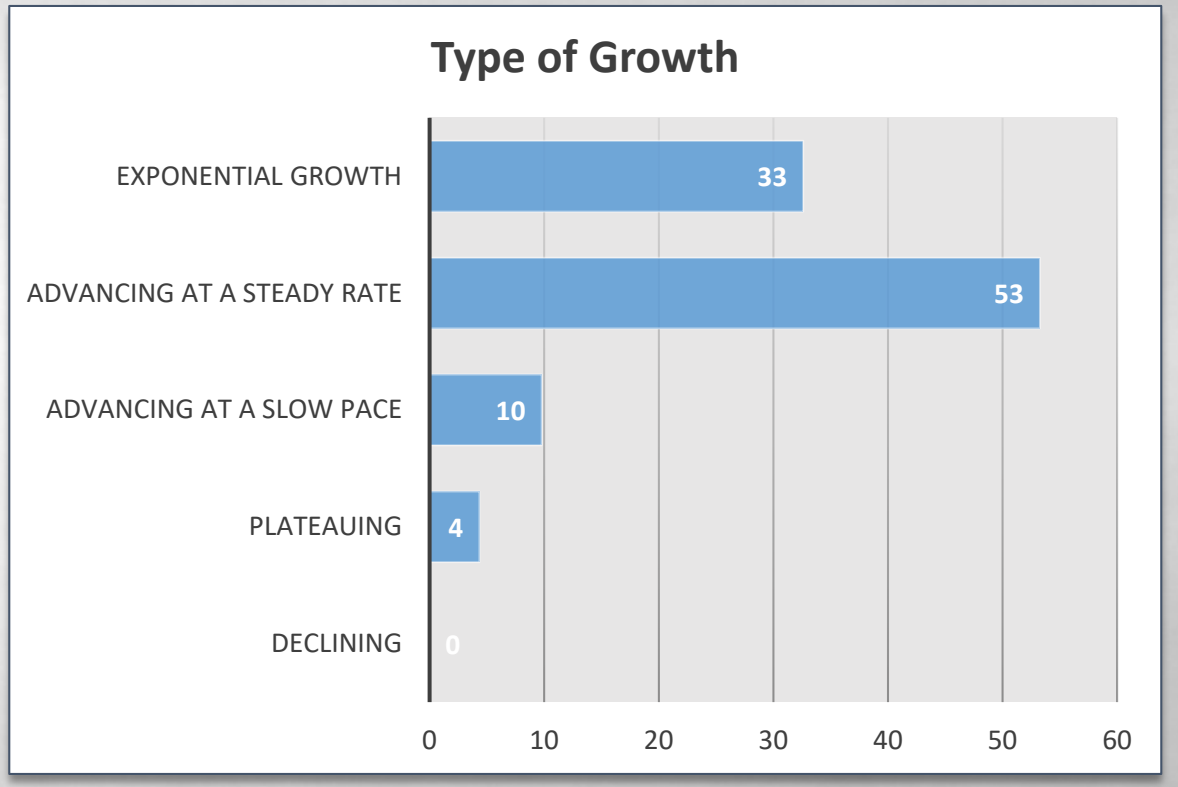
Risk of Misuse - AM





Governability - AM





Ranked for Risk of Misuse - AM

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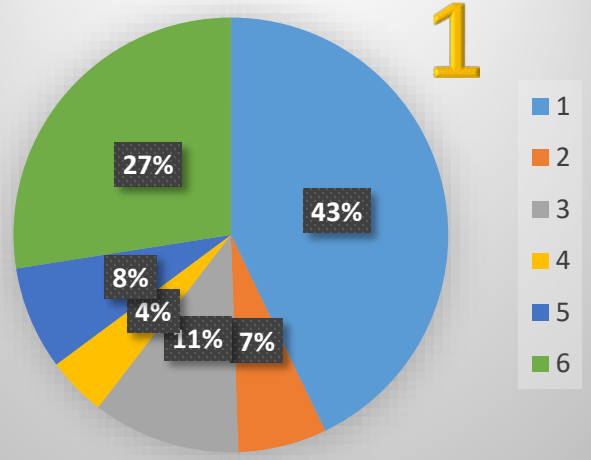
Weapons of Mass Destruction

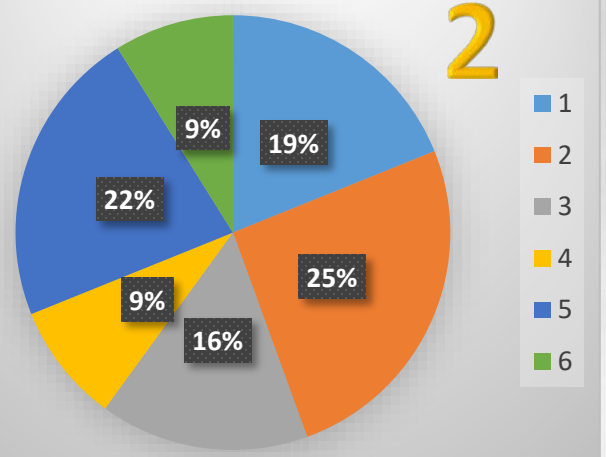
Bioprinting

1



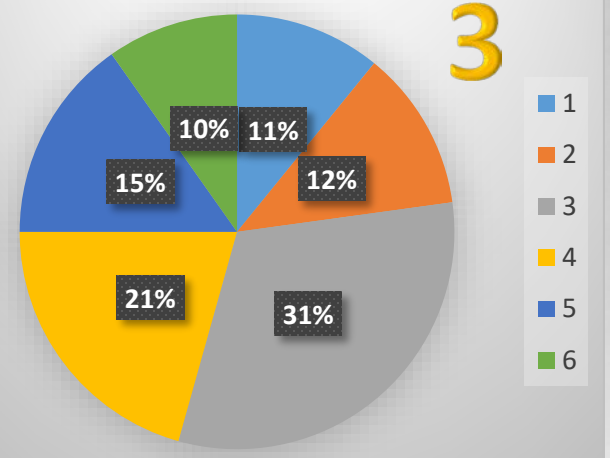
Microreactor

2



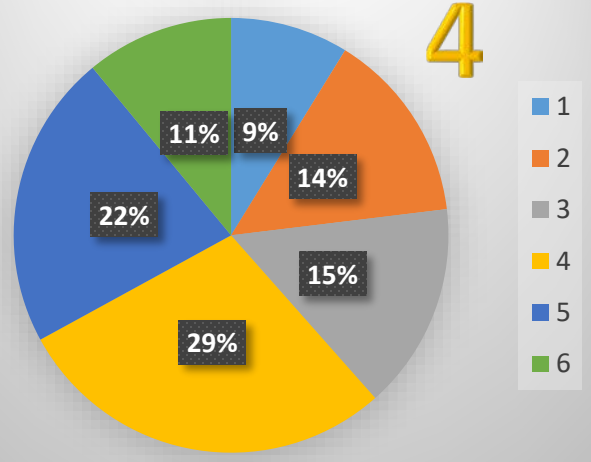
Material Extrusion

3



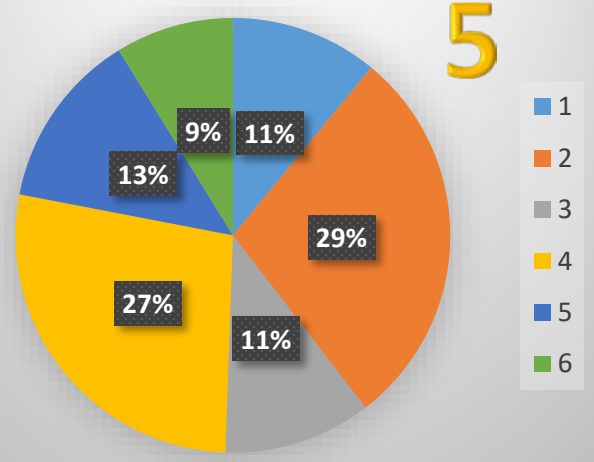
Material Jetting

4



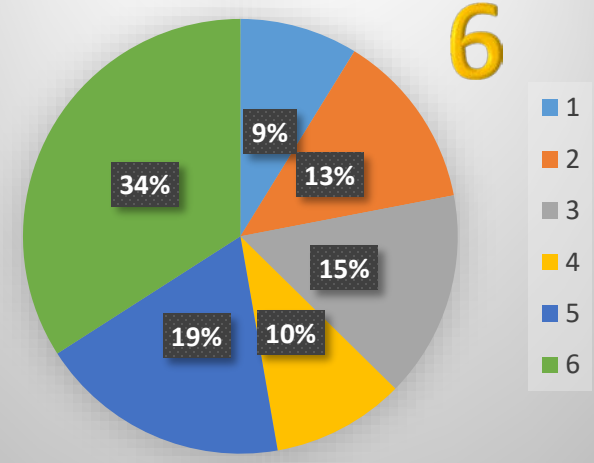
Carbon Fiber

5



Powder Bed Fusion

6



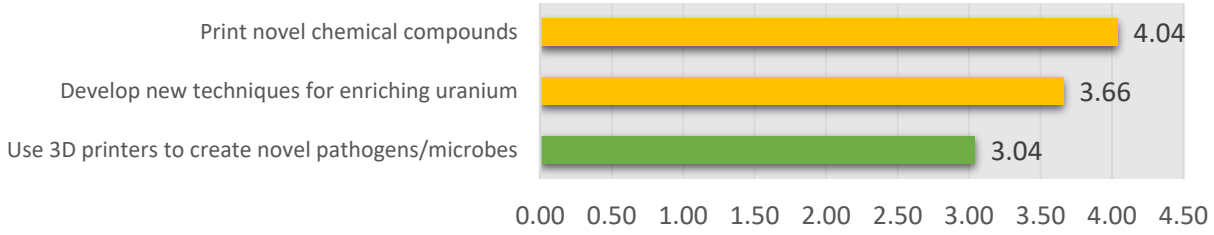
Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

WMD Pathways - AM

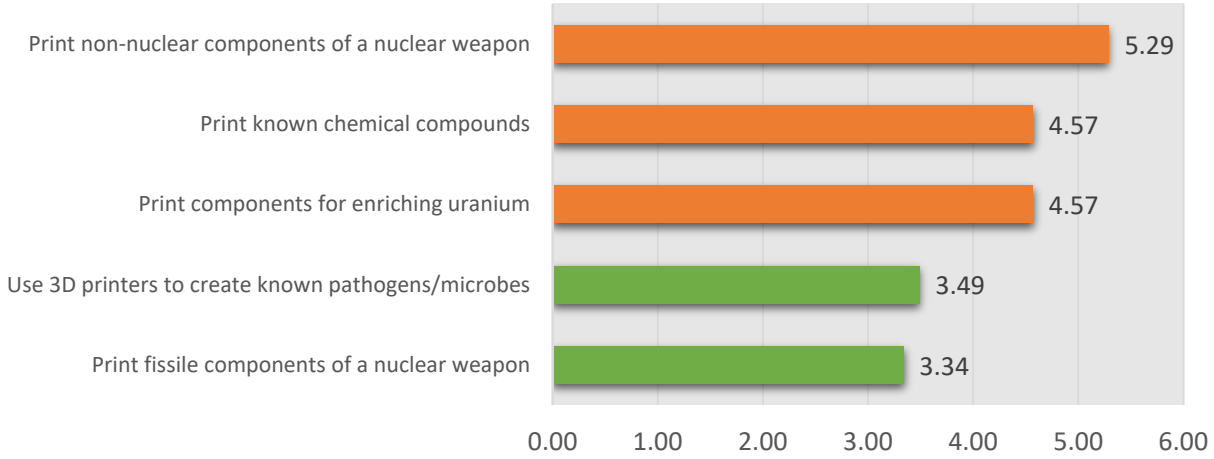
Center for the Study of WMD — Weapons of Mass Destruction

State Actors

Research and Development

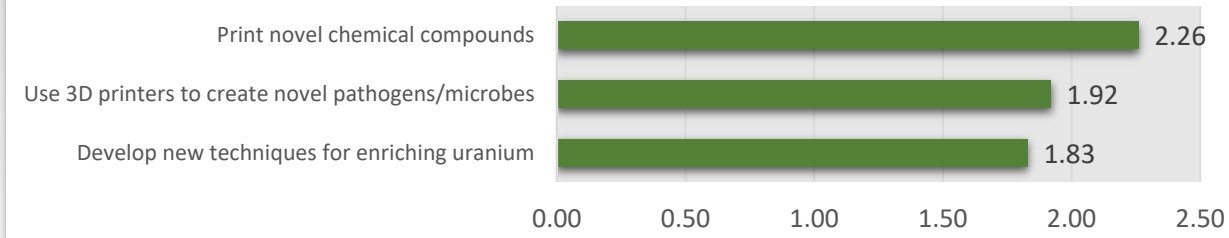


Acquisition and Production

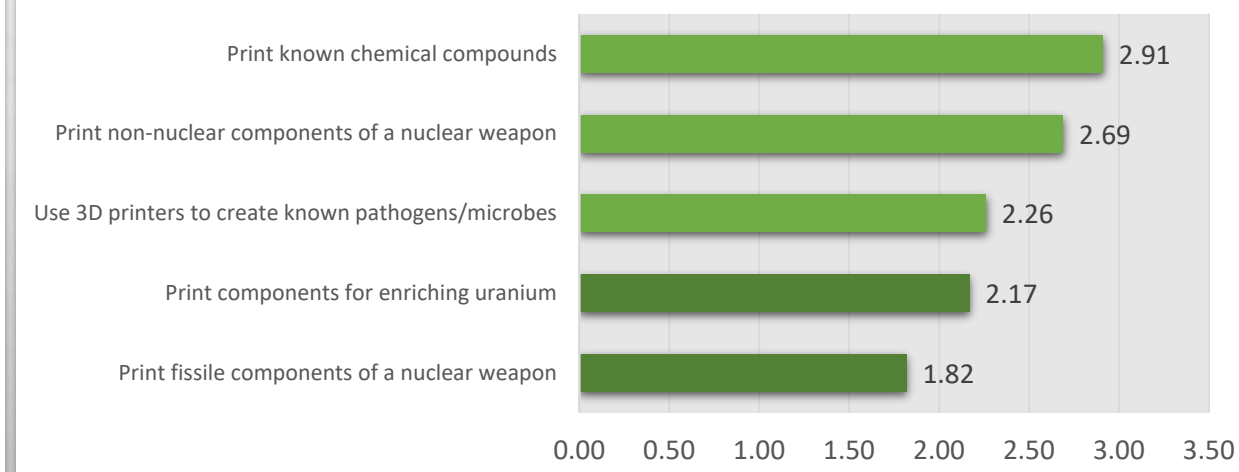


Non-state Actors

Research and Development



Acquisition and Production

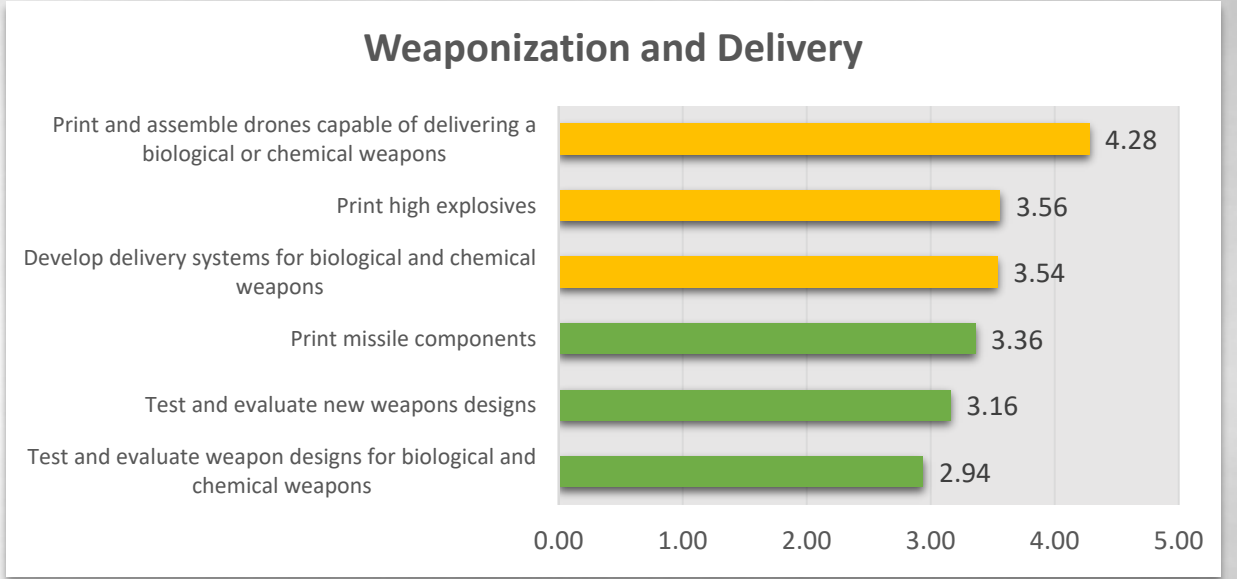


Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

WMD Pathways - AM

State Actors

Non-state Actors



Other Enabling Effects – AM

Respondents suggested that we missed several enabling effects of additive manufacturing for development or use of WMD

Weaponization and Delivery:

- Printing cell or organ systems to test toxicity, pathogenicity, and "effectiveness" of biological and chemical weapons
- Multi-material printing (especially electronics and electromagnetic devices) may facilitate the development of WMD delivery systems
- Aerosolization technologies for the delivery of stabilized pathogens/microbes

Advanced Robotics (AR)

Opportunities – AR

Detection

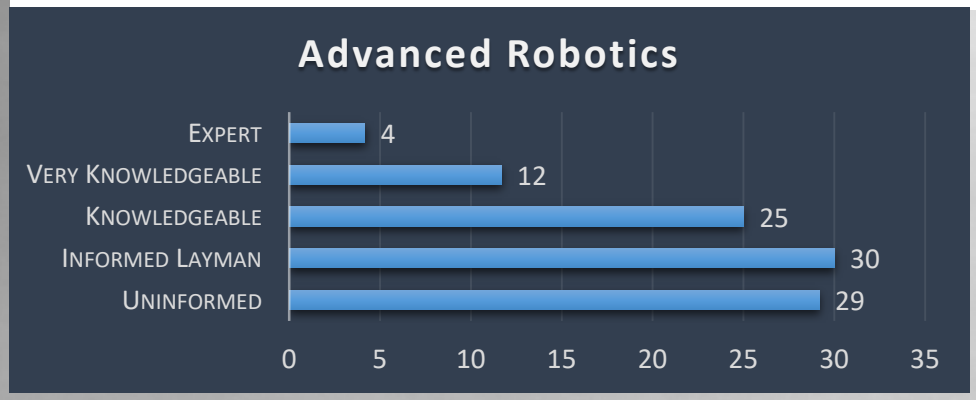
- Equip drones or other robotics with detectors to sense CBRN
- Enhanced surveillance of state and non-state actor activities
- Swarms of CBRN detectors to enable persistent surveillance

Response

- Use robotics to investigate a scene for CBRN contamination
- Rapid delivery of countermeasures (e.g., treatment after a biological attack)
- Use robotics for decontamination after a CBRN attack

Heat Map - AR

	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Advanced Robotics											
Advanced States	5.13	6.32	5.36	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Developing States	3.20	3.96	3.85	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Non-State Actors	2.93	3.27	3.27	4.26	4.41	4.04	5.44	5.43	5.38	4.55	4.90
Autonomous Systems		3.93	4.72	4.23	5.18		4.64				
Strong AI		3.04	3.91	3.12	5.32		2.95				
UAVs		6.32	6.28	5.91	5.47		6.63				
Weak AI		4.92	4.41	4.36	3.96		5.45				



Average Score	Color*
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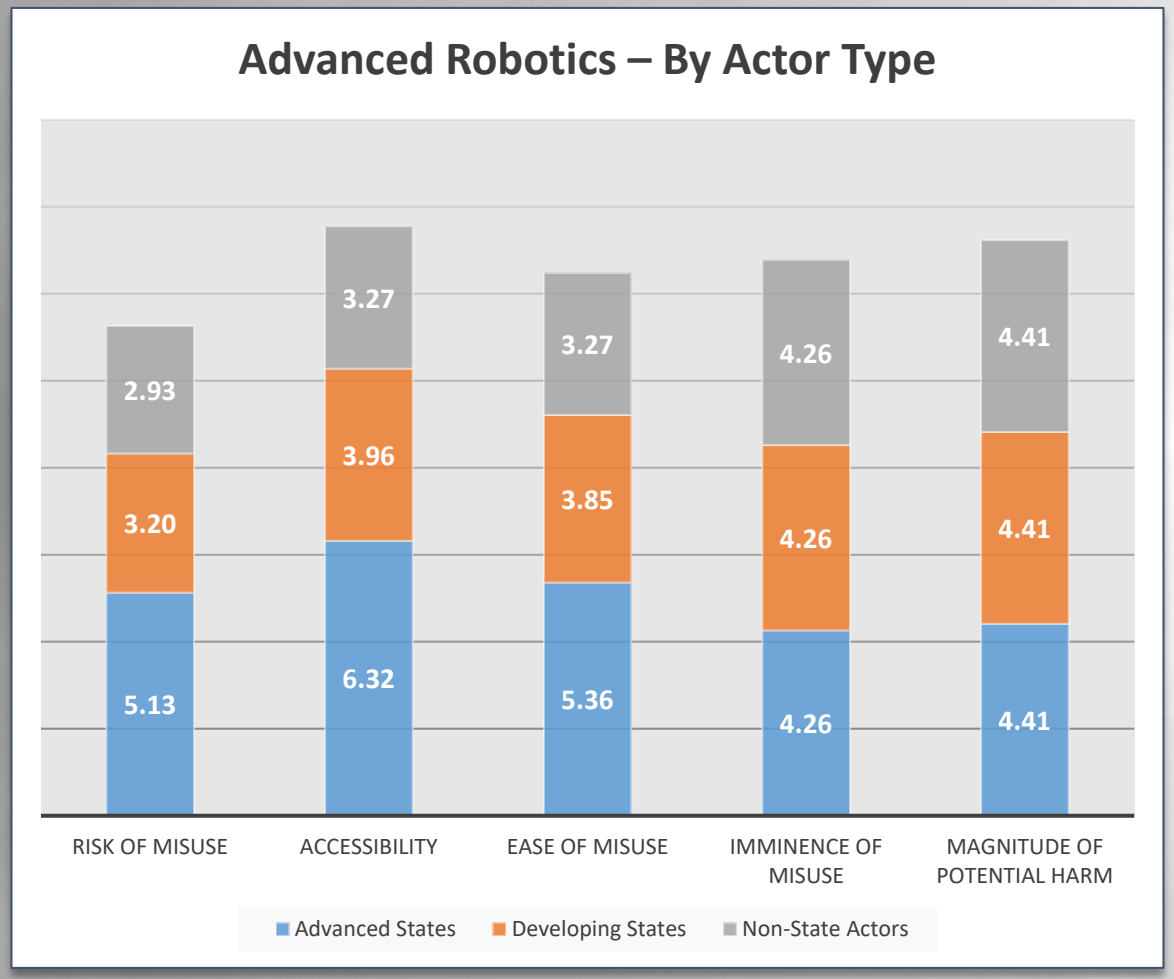
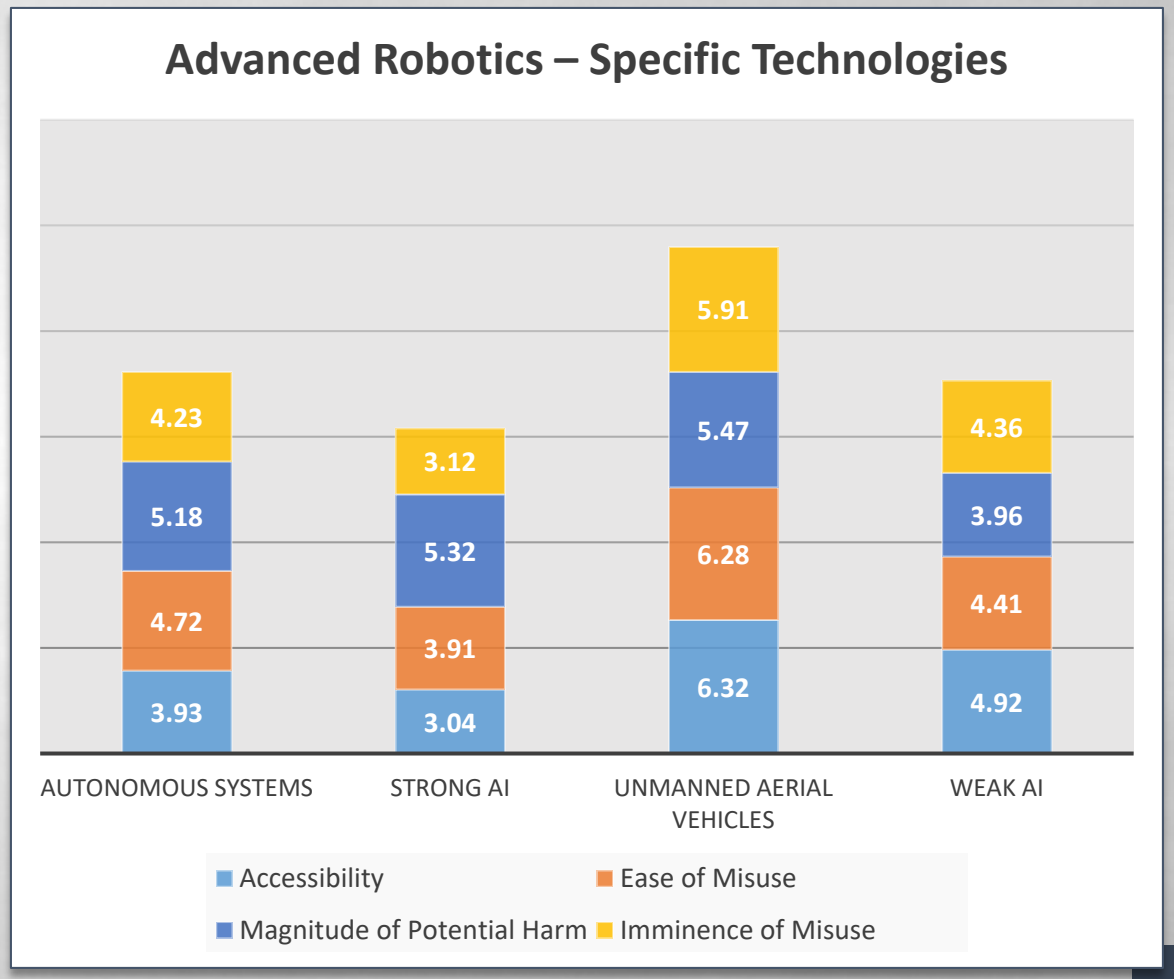
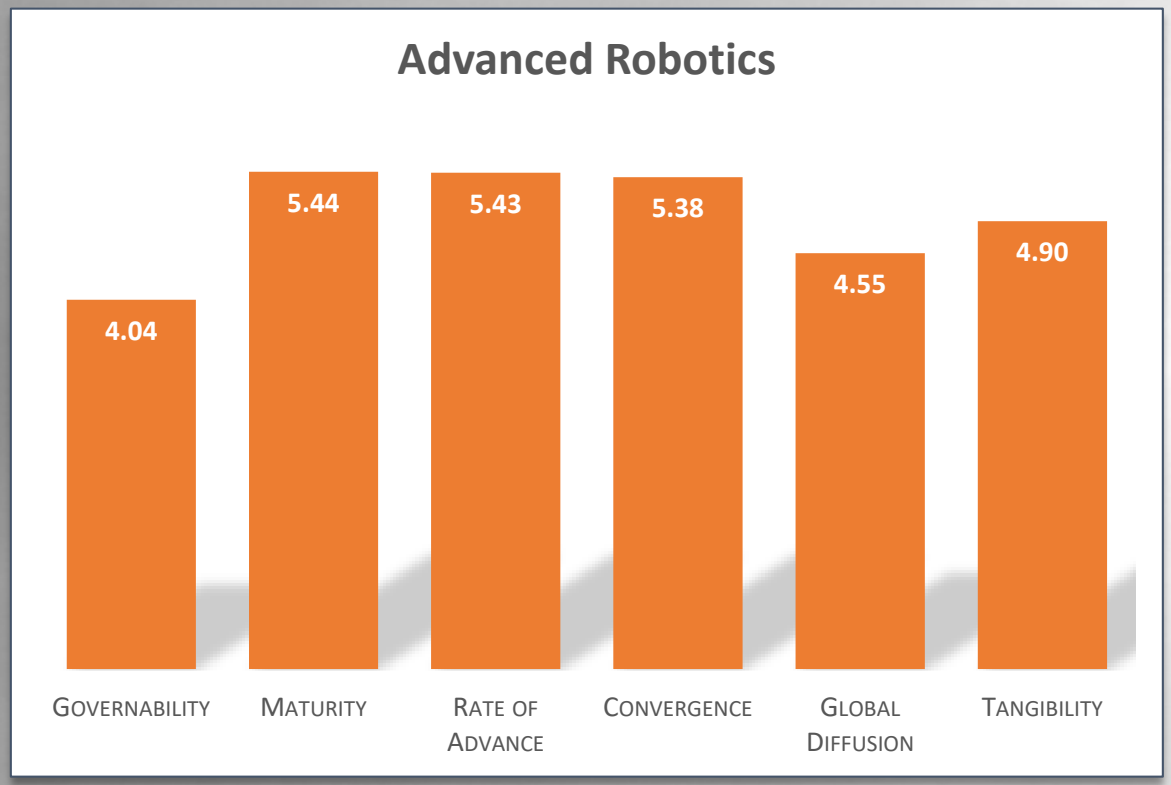
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

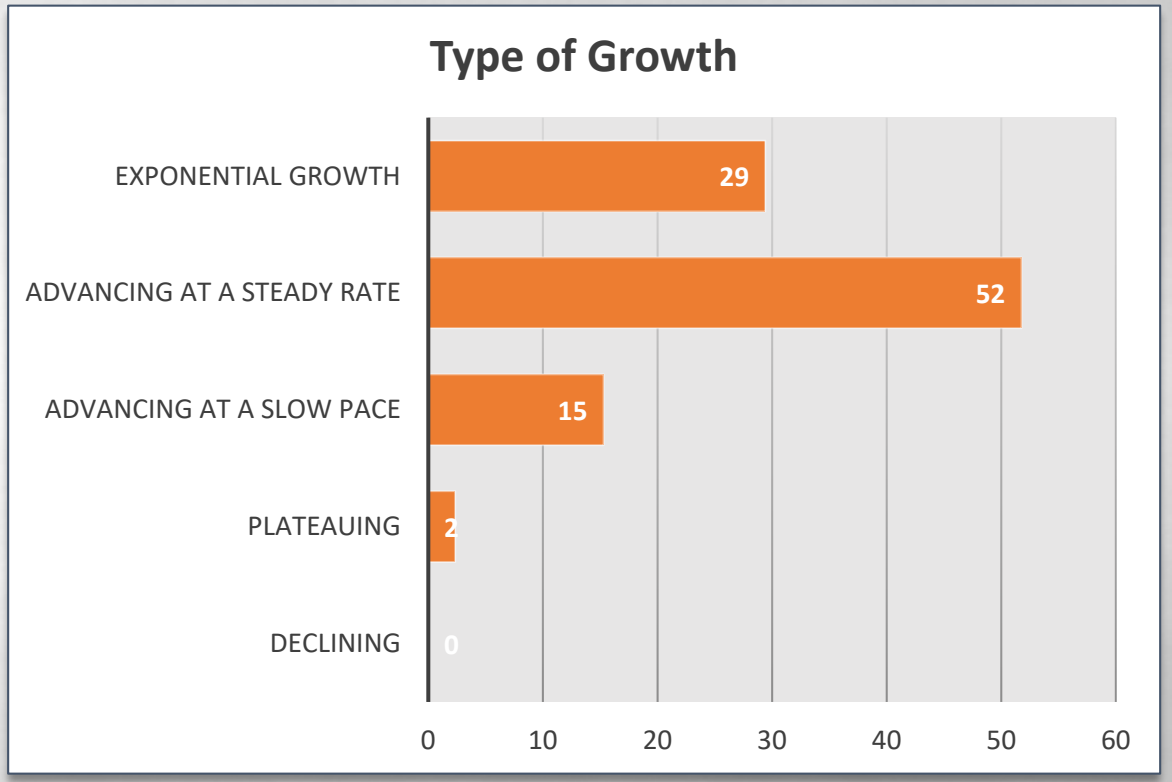
Risk of Misuse - AR



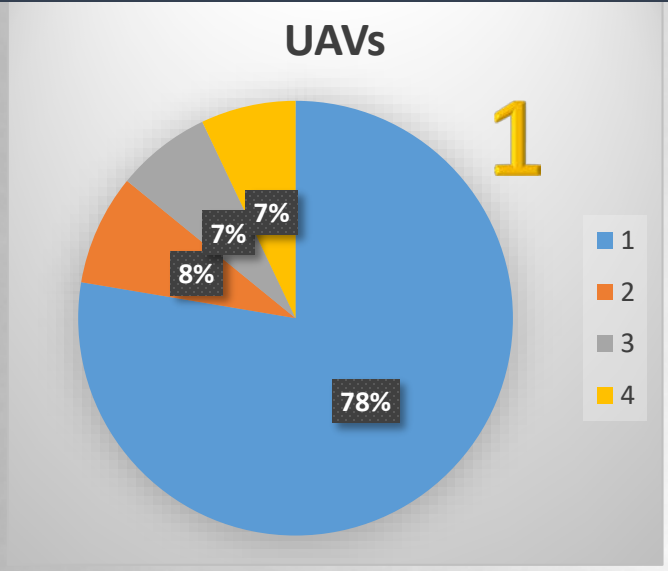


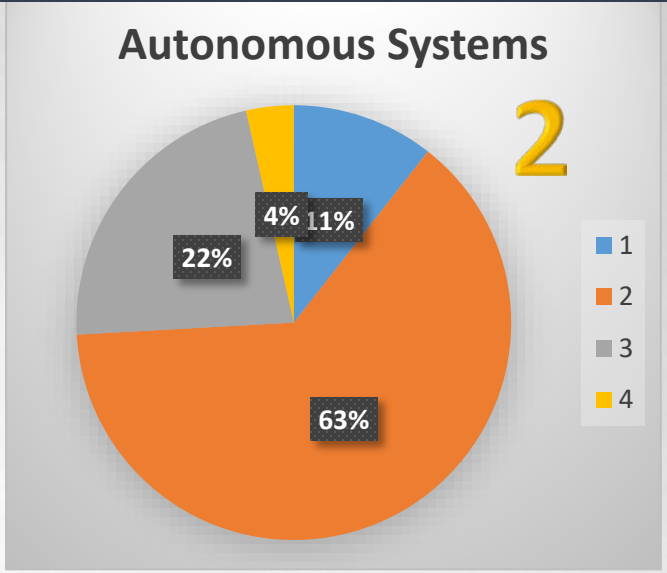
Governability - AR

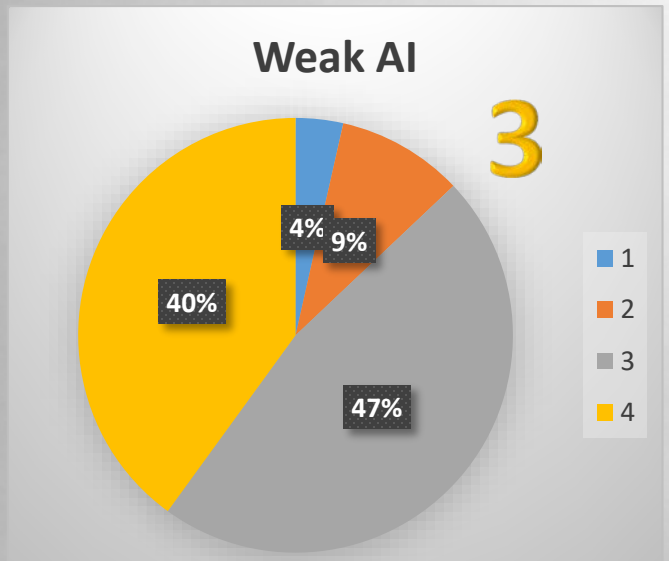


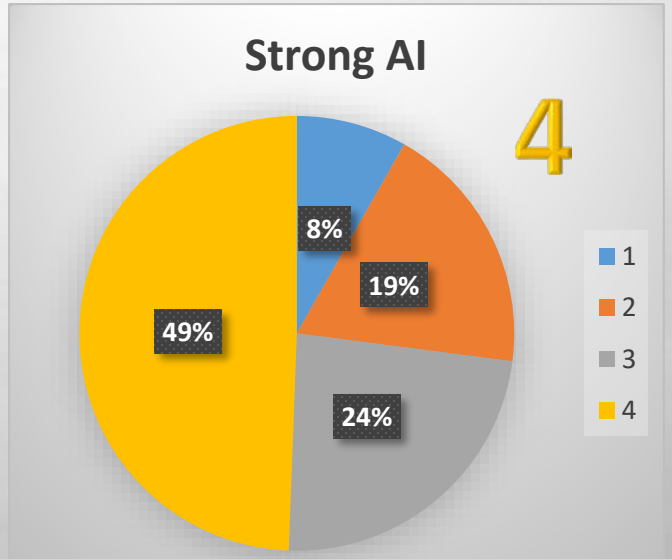


Ranked for Risk of Misuse - AR





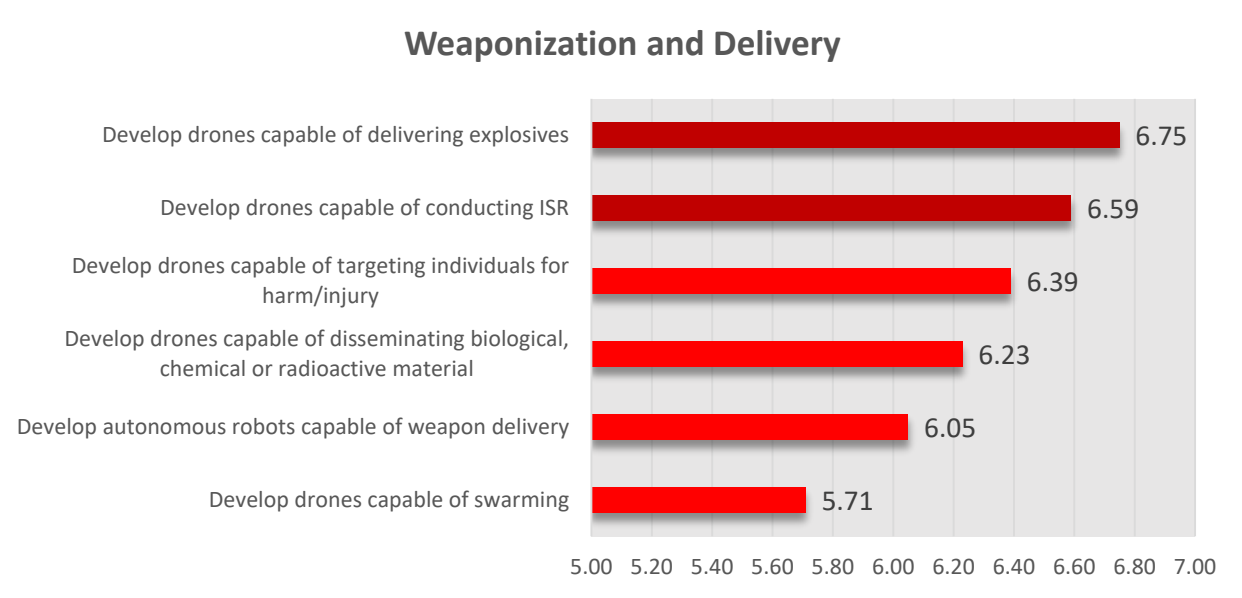




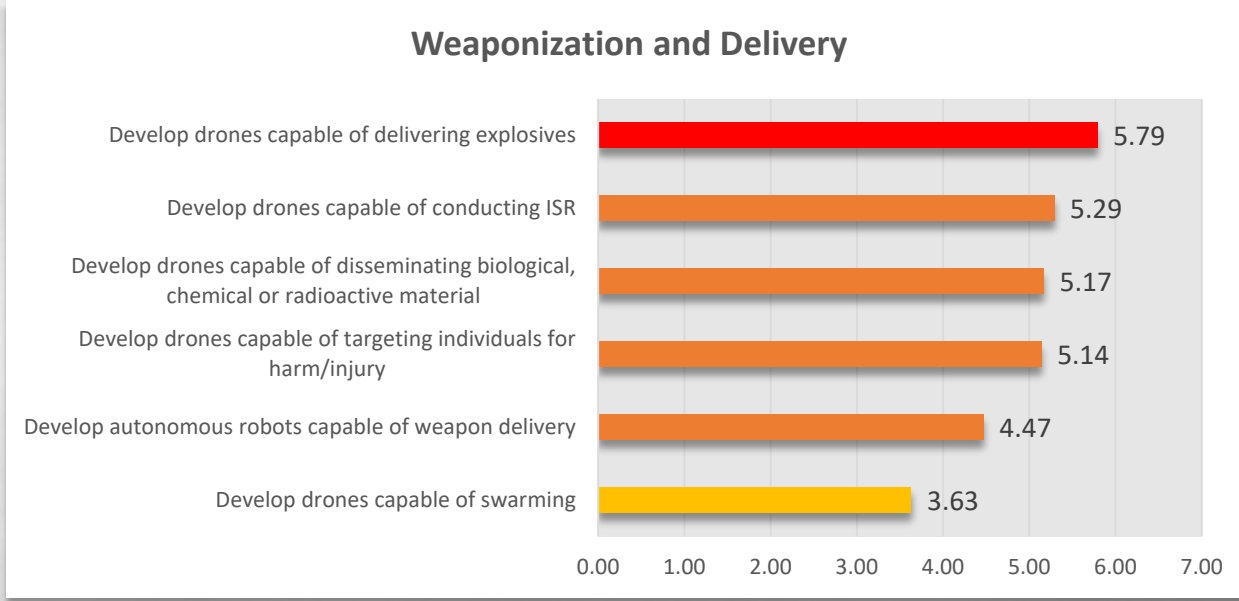
Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

WMD Pathways - AR

State Actors



Non-state Actors



Other Enabling Effects - AR

Respondents suggested that we missed several enabling effects of advanced robotics for development or use of WMD

Weaponization and Delivery:

- Use of unmanned ground vehicles for delivery of explosives and/or WMD
- UAVs as a potential weapon against aircraft
- Use of simulation/modeling to determine WMD effects for purposes of targeting
- Delivery of biological agents against agriculture (plants and animals)

Nanotechnology (Nano)

Opportunities - Nano

Detection

- Sensors for environmental detection
- Nanotechnology-based tags applied to dual-use components to enhance export control efforts and IAEA safeguards

Countermeasures

- Catalytic nanomaterials for degrading chemical agents, possibly for incorporation into PPE
- Increased stability of medical countermeasures (longer storage at ambient temperatures)
- Possible distribution of medical counter measures through water supply

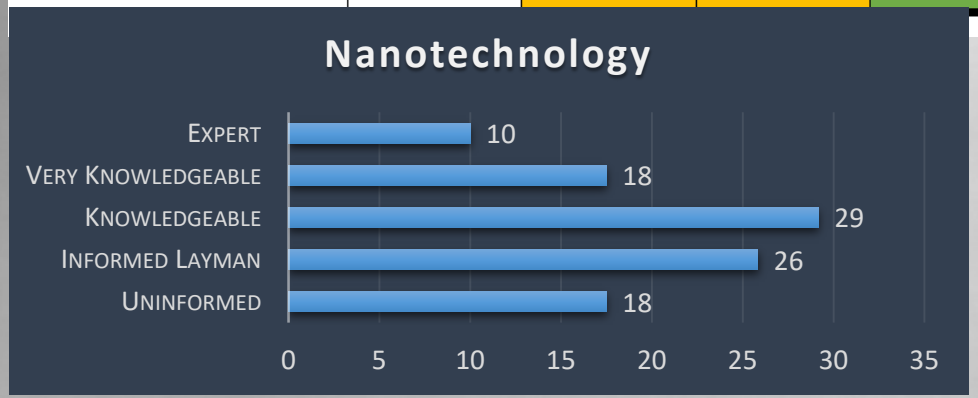
Response

- New materials for decontamination
- Improved delivery and targeting of medical countermeasures

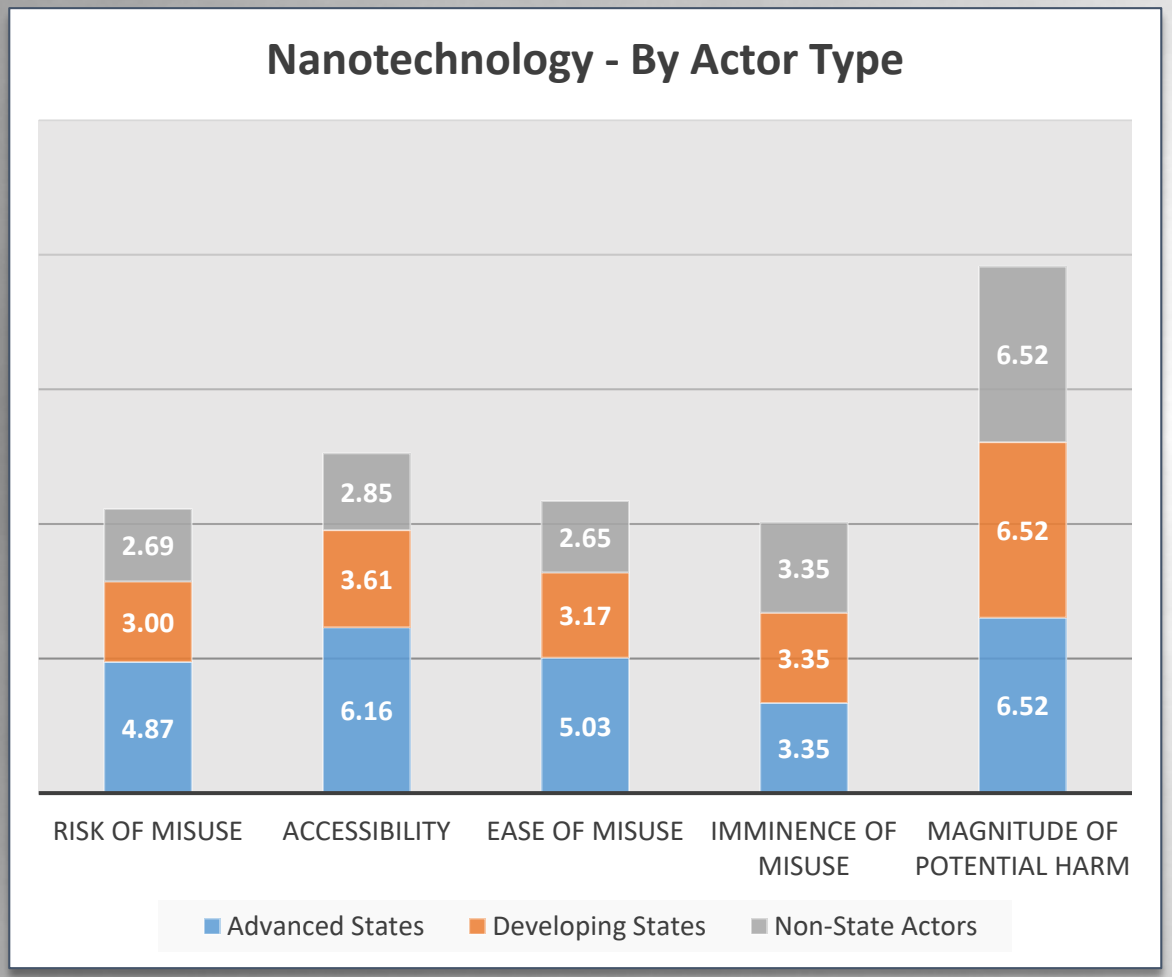
Heat Map - Nano

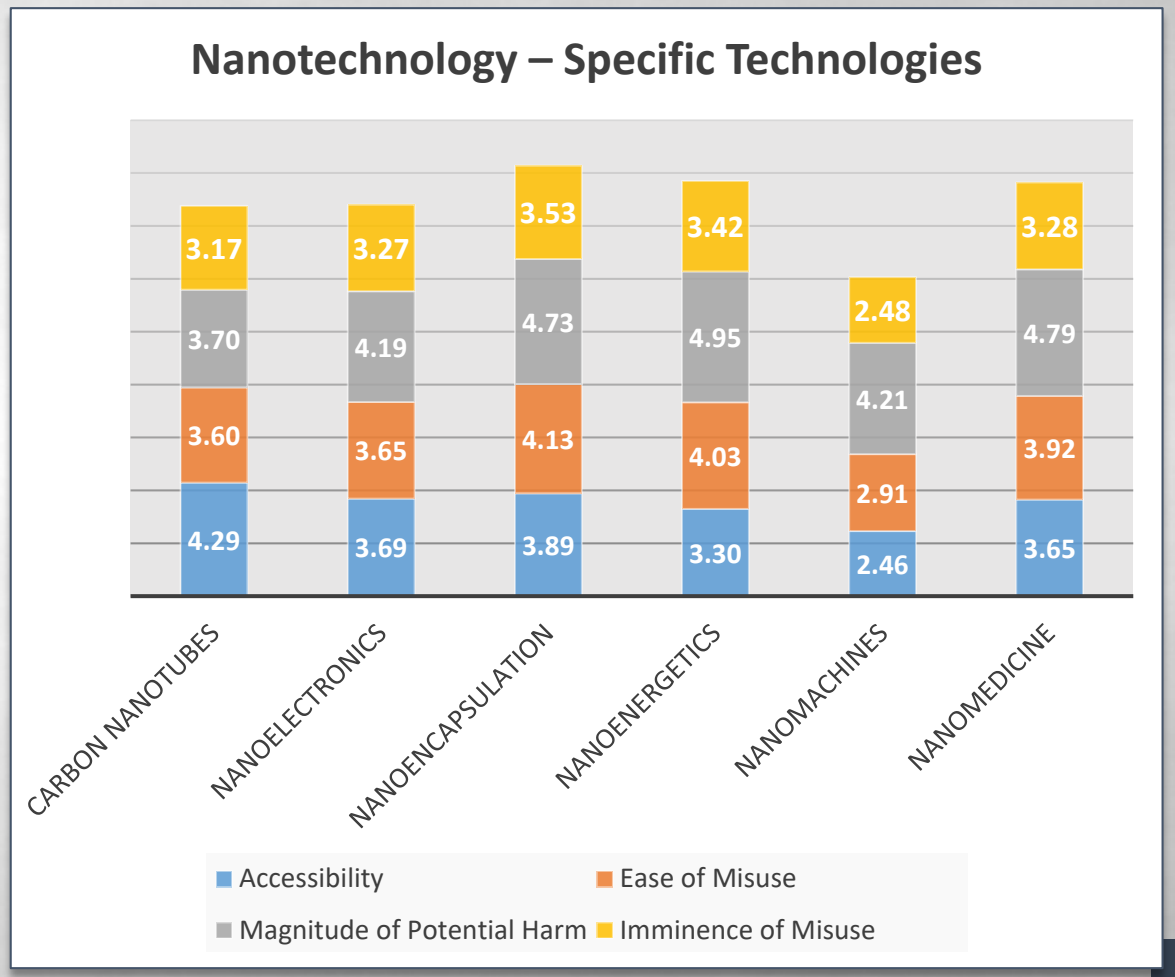
	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Nanotechnology											
Advanced States	4.87	6.16	5.03	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Developing States	3.00	3.61	3.17	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Non-State Actors	2.69	2.85	2.65	3.35	6.52	3.88	5.00	4.92	4.82	4.17	4.29
Carbon Nanotubes		4.29	3.60	3.17	3.70		5.52				
Nanoelectronics		3.69	3.65	3.27	4.19		4.75				
Nanoencapsulation		3.89	4.13	3.53	4.73		4.98				
Nanoenergetics		3.30	4.03	3.42	4.95		3.91				
Nanomachines		2.46	2.91	2.48	4.21		3.29				
Nanomedicine		3.65	3.92	3.28	4.79		4.67				

Average Score	Color*
1.0 – 1.49	
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

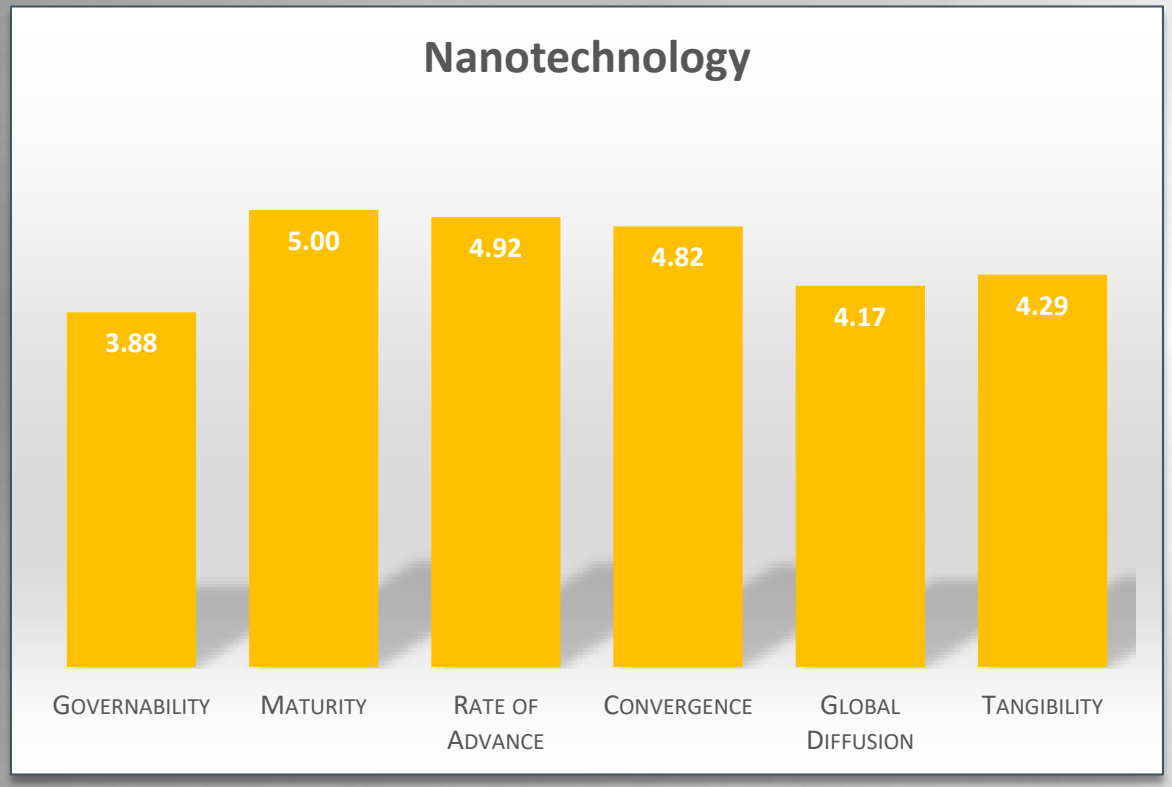


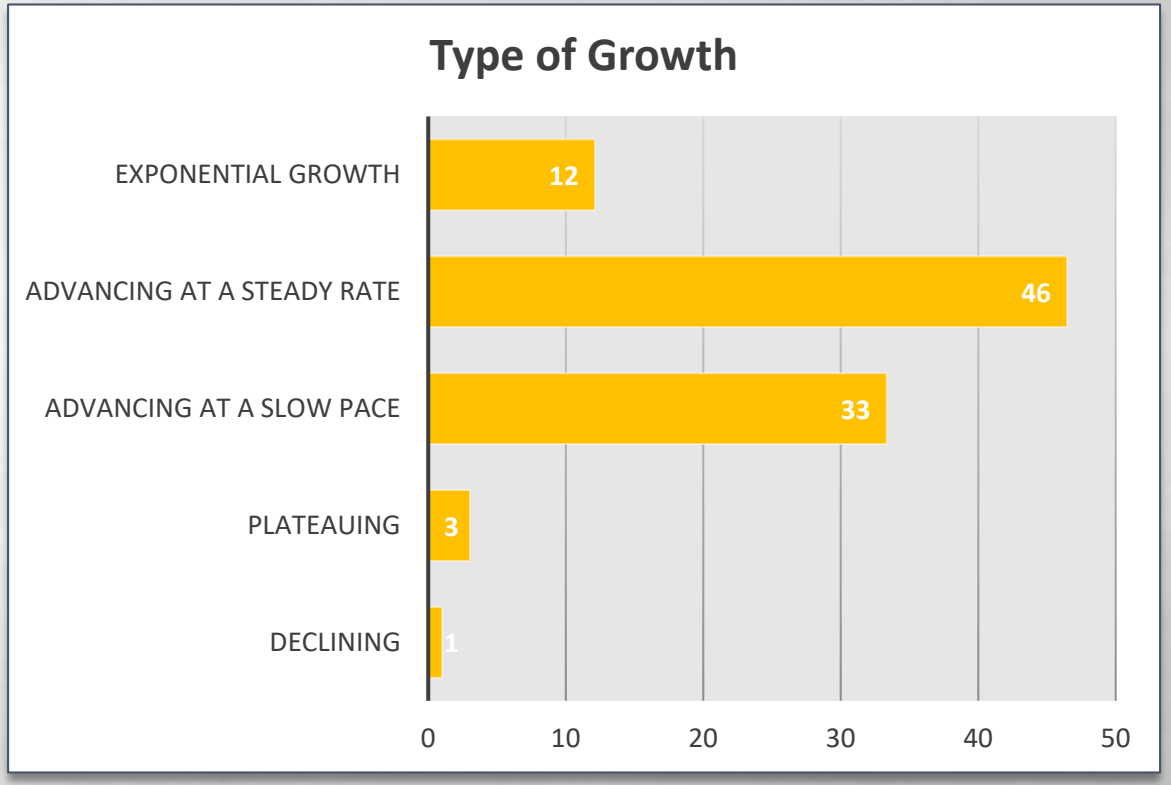
Risk of Misuse - Nano





Governability - Nano

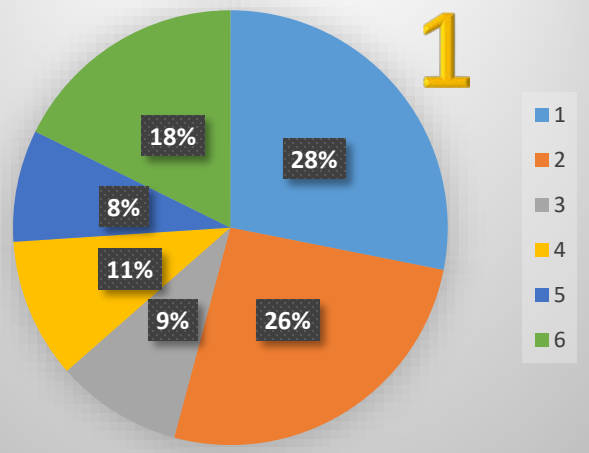




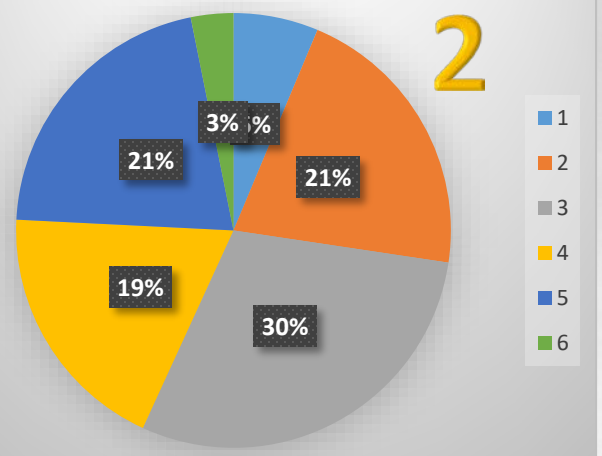
Ranked for Risk of Misuse - Nano

Center for the Study of WMD
Weapons of Mass Destruction

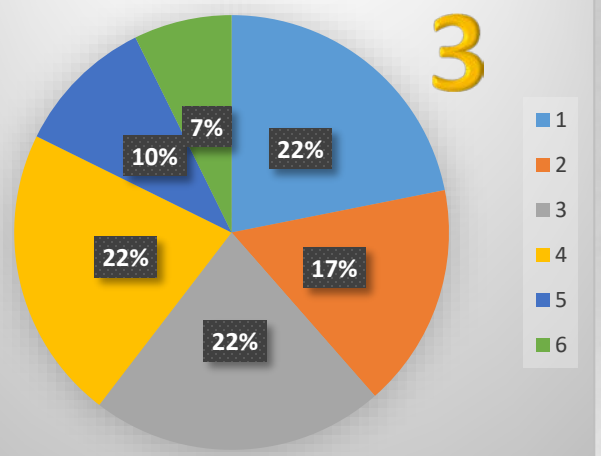
Nanomedicine



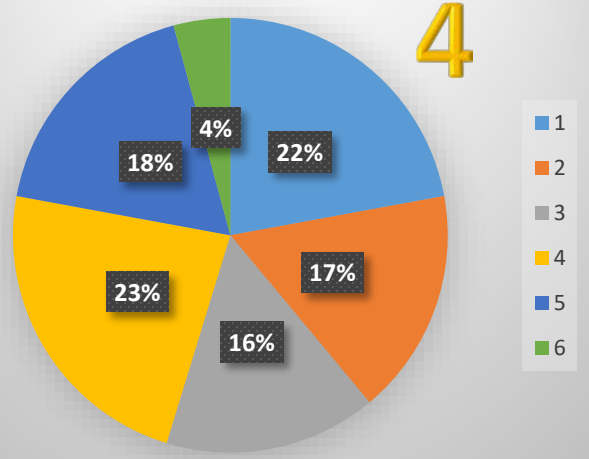
Nanoelectronics



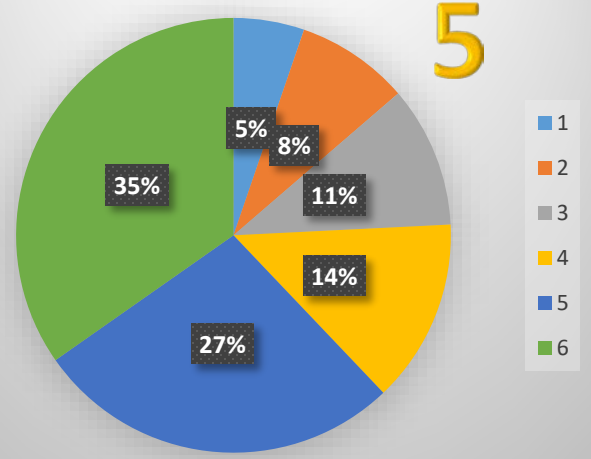
Nanoencapsulation



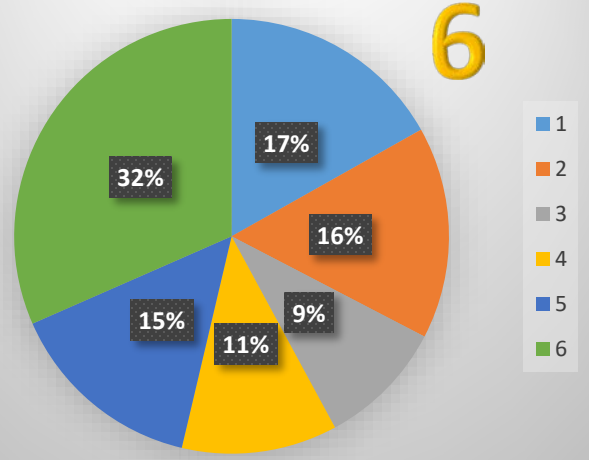
Nanoenergetics



Nanomachines



Carbon Nanotubes

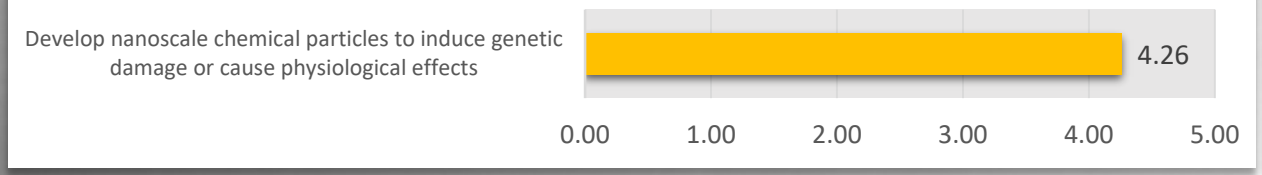


Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

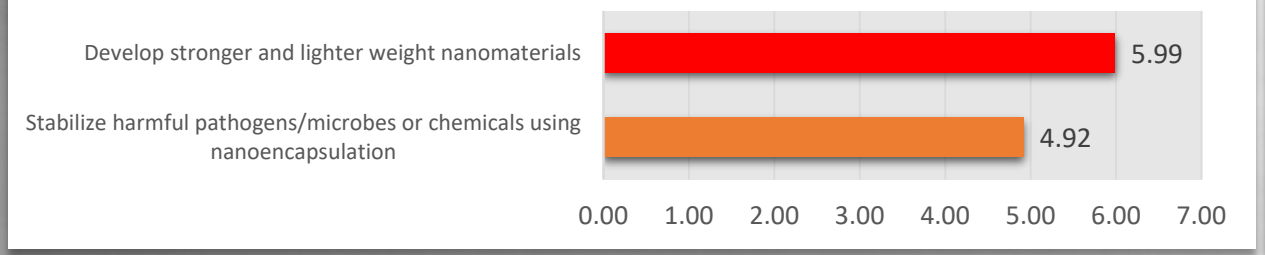
WMD Pathways - Nano

State Actors

Research and Development

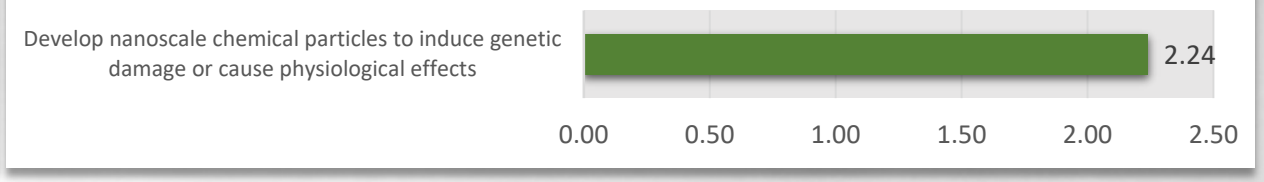


Acquisition and Production

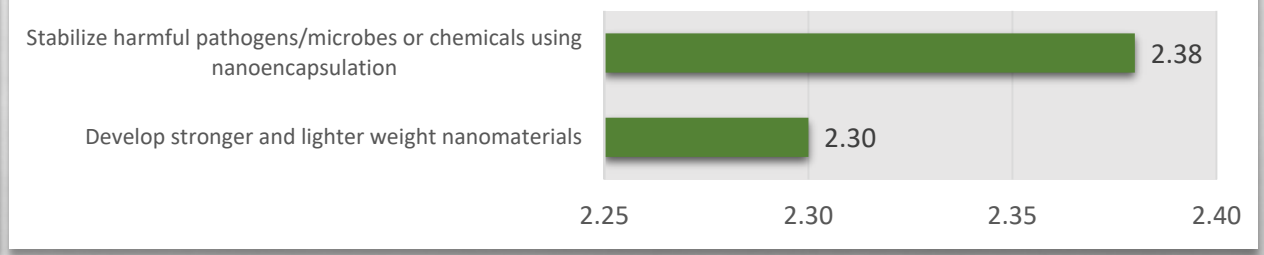


Non-state Actors

Research and Development



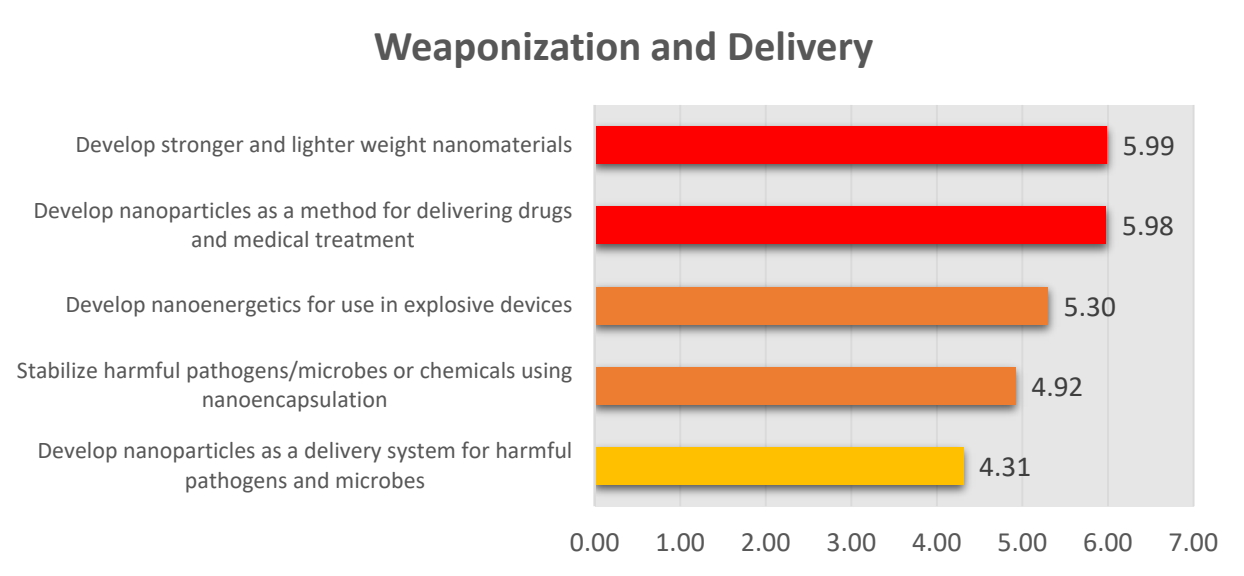
Acquisition and Production



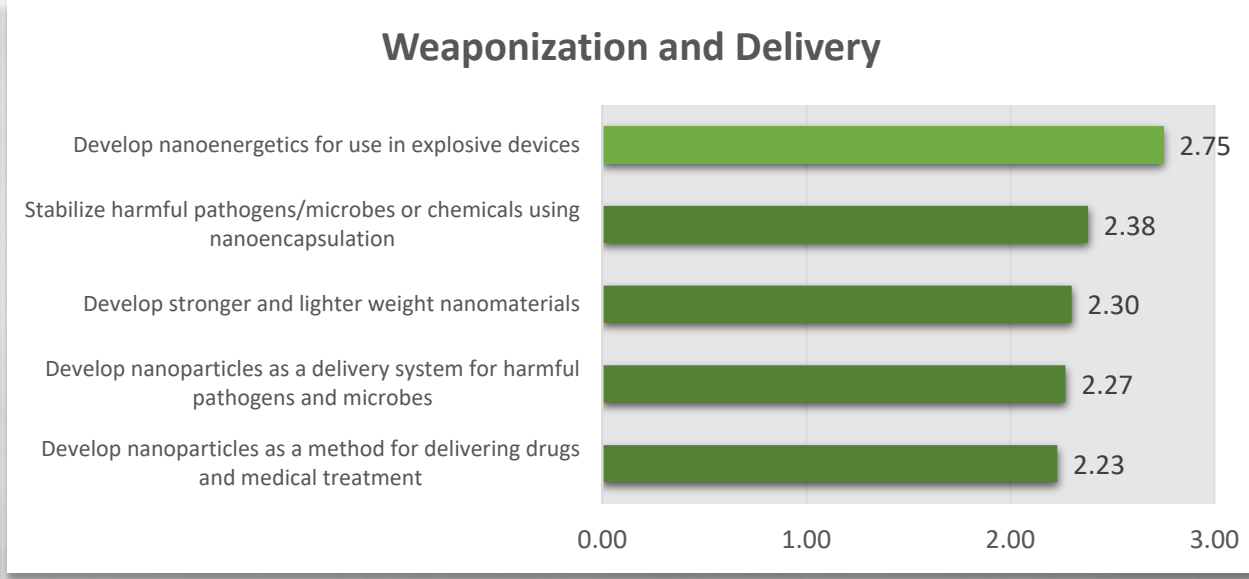
Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

WMD Pathways - Nano

State Actors



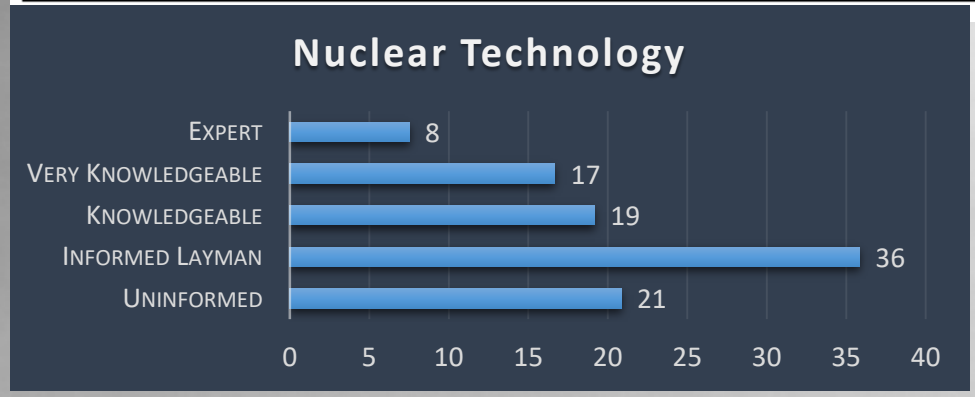
Non-state Actors



Nuclear Technology (NT)

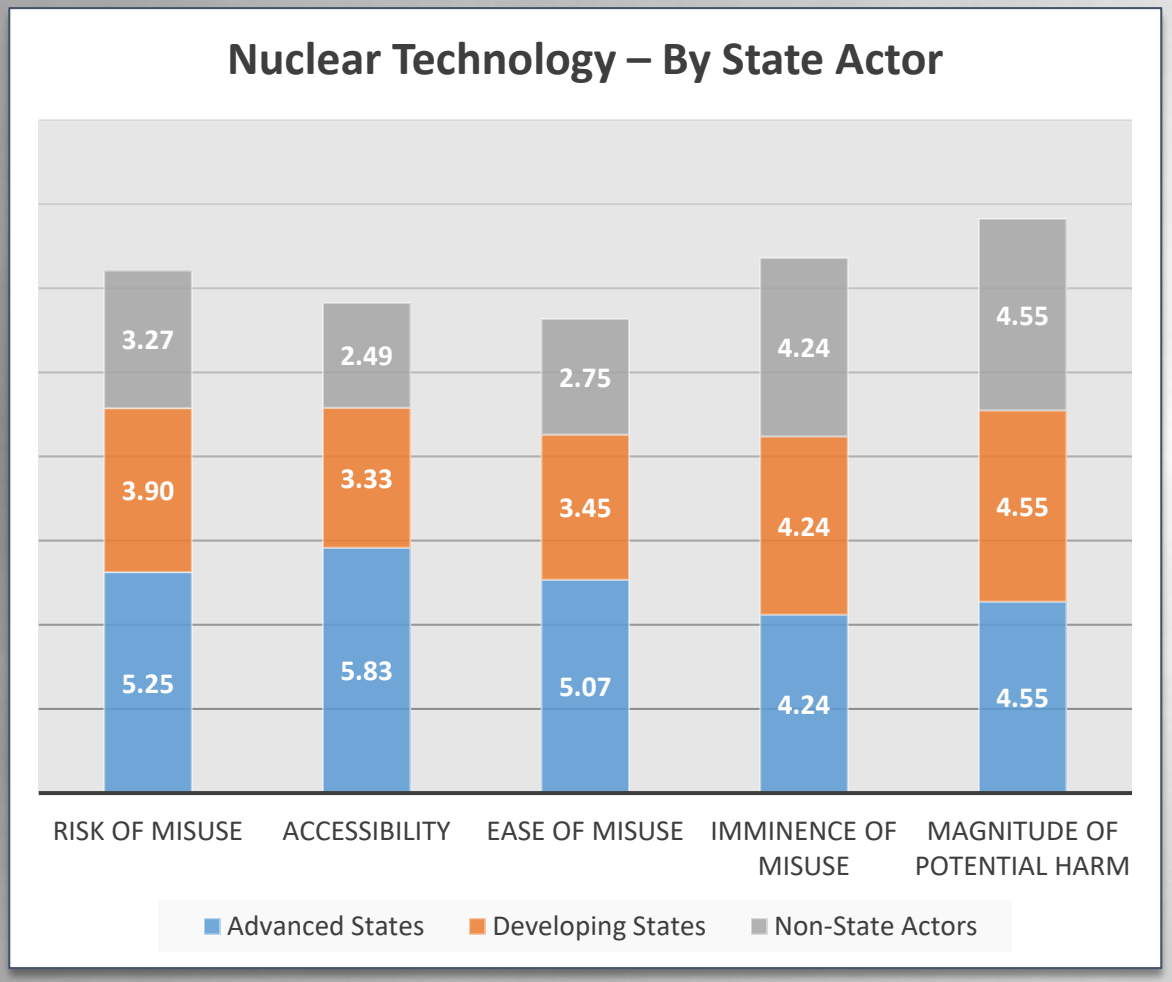
Heat Map - NT

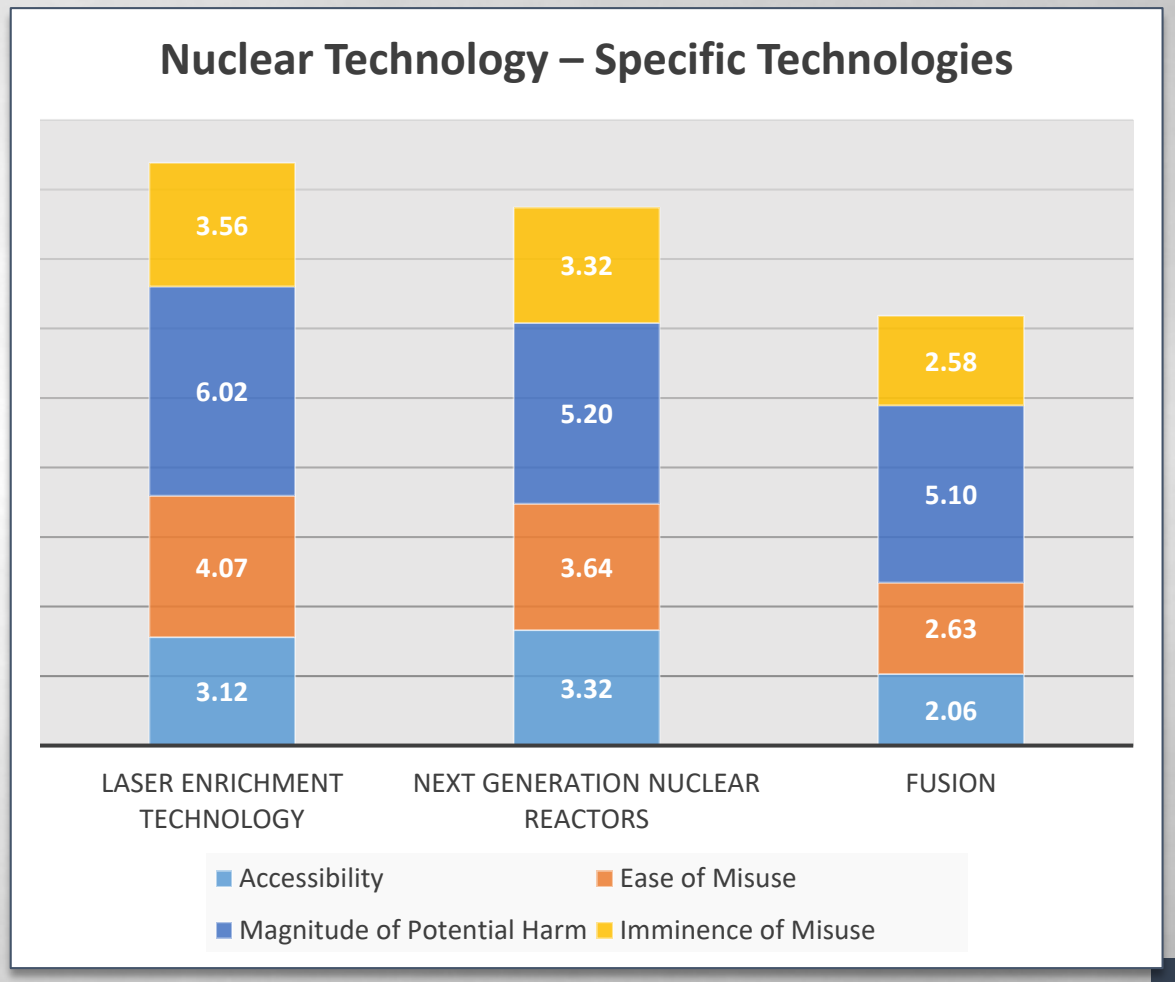
	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Nuclear Technology											
Advanced States	5.25	5.83	5.07	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Developing States	3.90	3.33	3.45	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Non-State Actors	3.27	2.49	2.75	4.24	4.55	5.86	6.02	3.88	3.47	3.70	5.59
Laser Enrichment		3.12	4.07	3.56	6.02		4.44				
NextGen Reactors		3.32	3.64	3.32	5.20		4.58				
Nuclear Fusion		2.06	2.63	2.58	5.10		3.11				



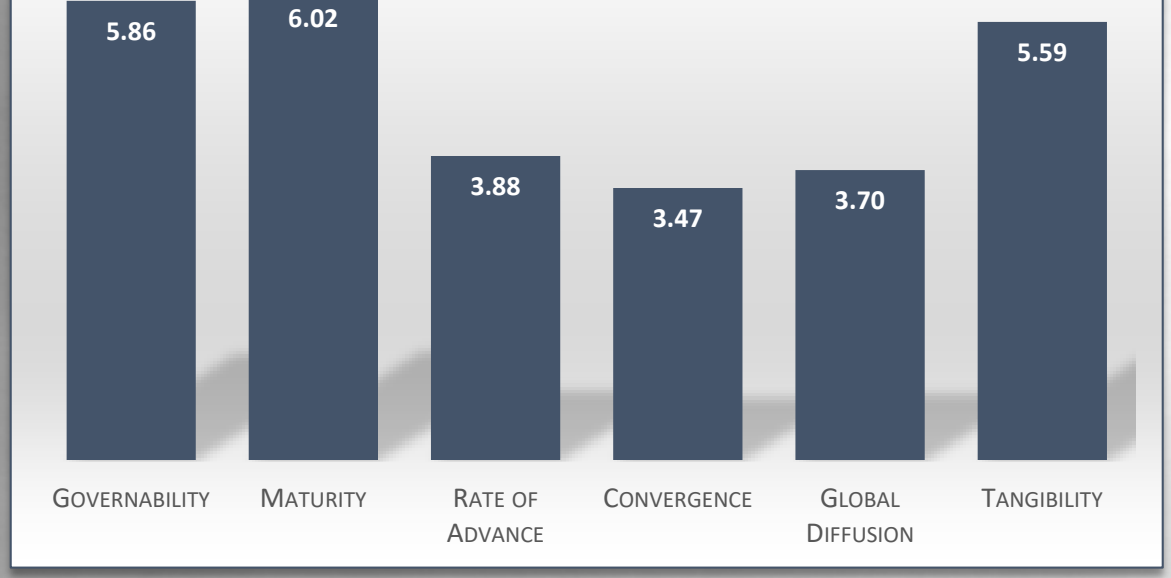
Average Score	Color*
1.0 – 1.49	
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

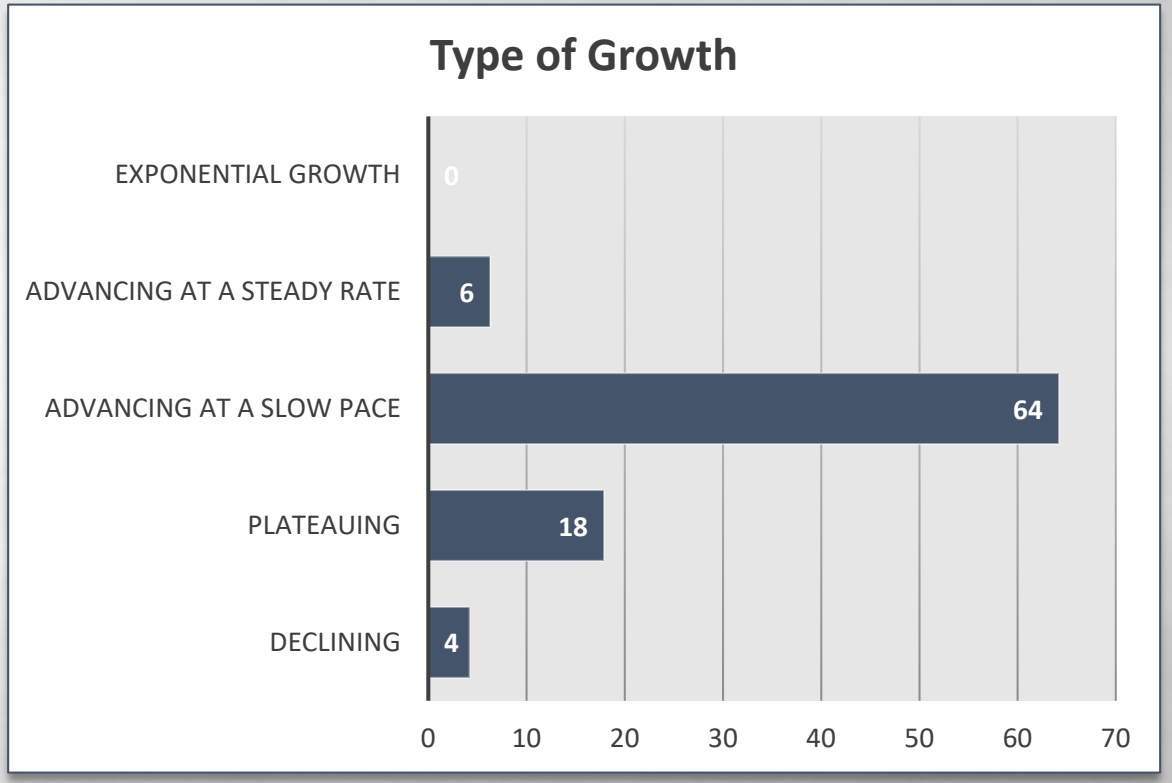
Risk of Misuse - NT



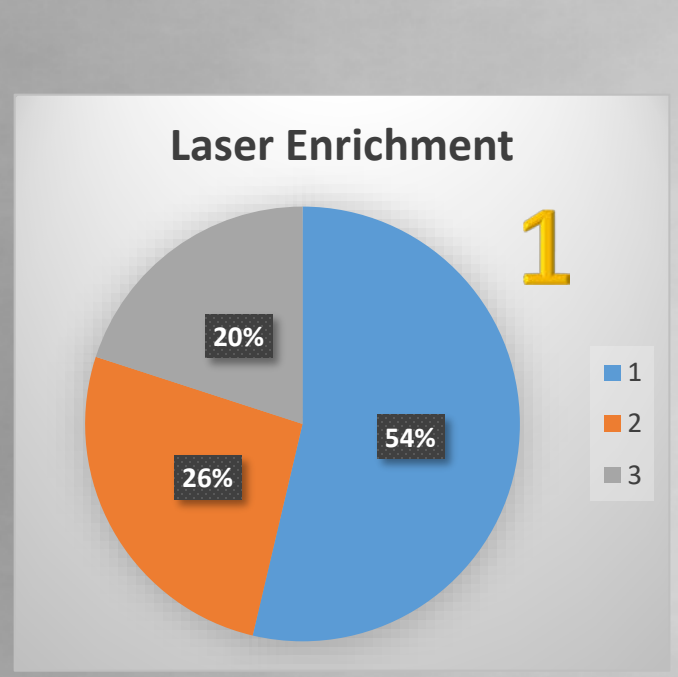


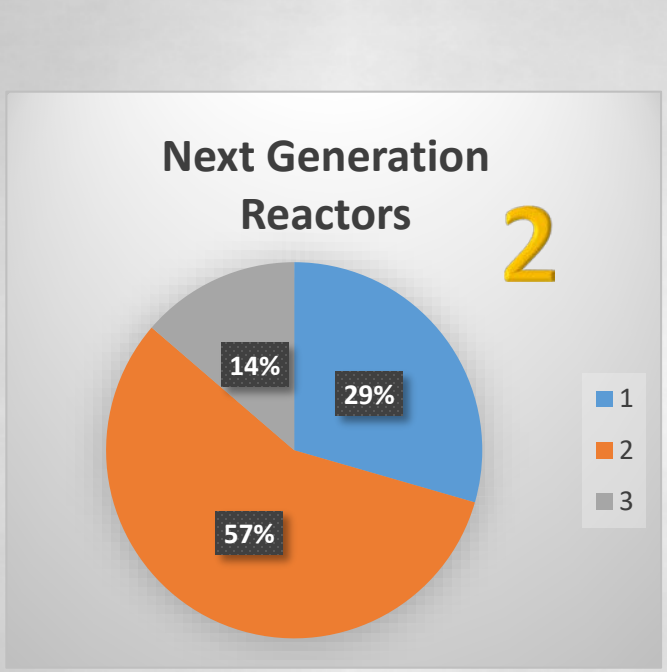
Governability - NT

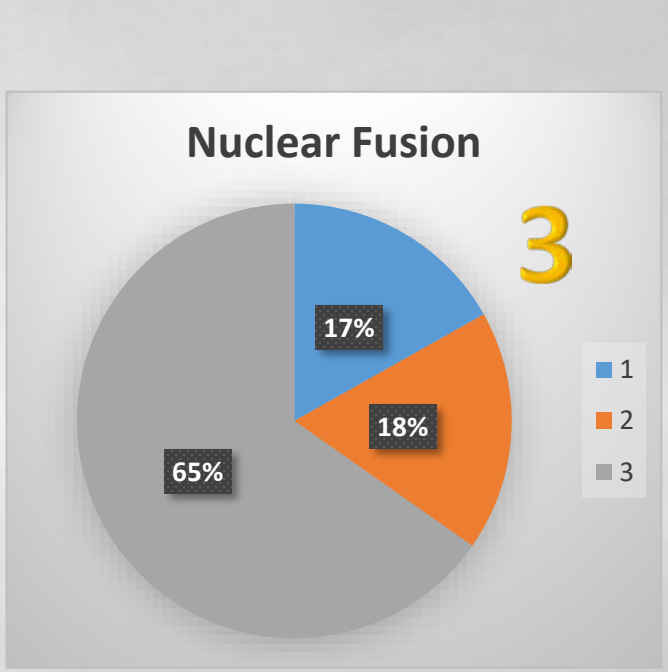




Ranked for Risk of Misuse - NT







Synthetic Biology (SynBio)

Opportunities – SynBio

Detection

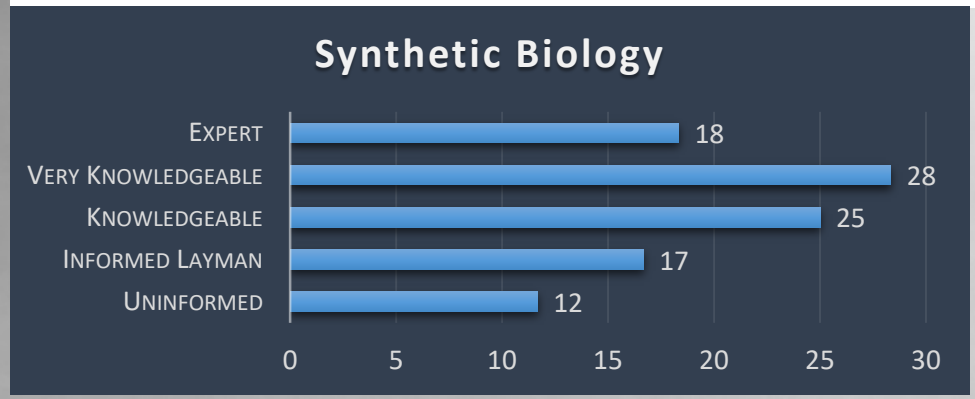
- Enhanced environmental sensing capabilities and surveillance
- New detection capabilities
- Rapid threat analysis and enhanced diagnostics

Countermeasures

- Development of vaccines, anti-bacterials, and therapeutics
- Faster, cheaper production of existing vaccines and anti-bacterials
- Targeted drugs and treatment through precision medicine

Heat Map – SynBio

	Risk of Misuse	Accessibility	Ease of Misuse	Imminence of Misuse	Magnitude of Harm	Governability	Maturity	Rate of Advance	Convergence	Global Diffusion	Tangibility
Synthetic Biology											
Advanced States	5.33	6.35	5.56	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85
Developing States	3.91	4.67	4.14	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85
Non-State Actors	3.95	4.21	3.77	4.29	5.93	3.03	5.44	6.04	5.13	5.15	3.85
Bioinformatics		5.41	4.28	3.77	4.43		6.27				
CRISPR/Gene Editing		5.28	4.74	4.02	5.55		5.69				
Gene Drives		4.09	3.98	3.51	5.49		4.04				
Precision Medicine		3.55	3.14	2.71	4.25		4.19				



Average Score	Color*
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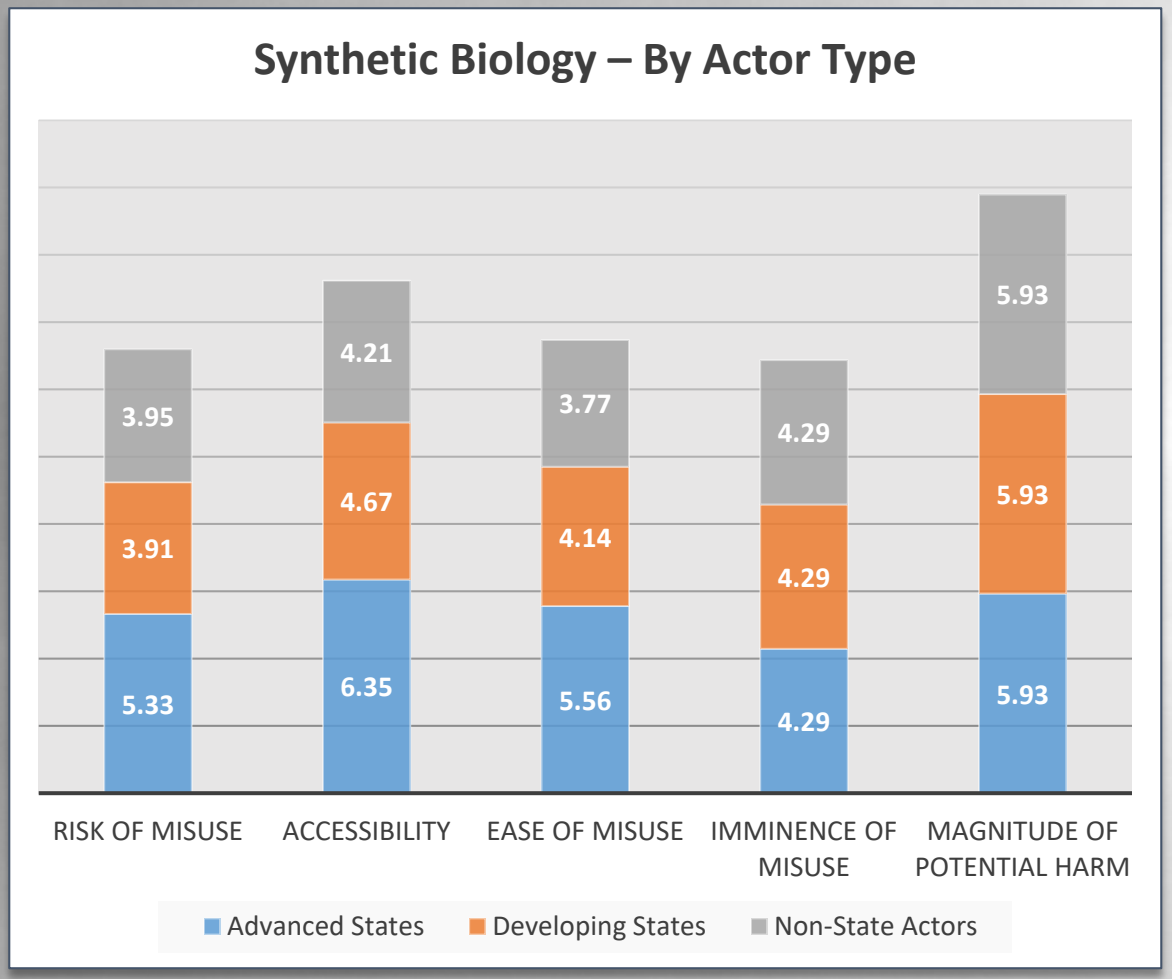
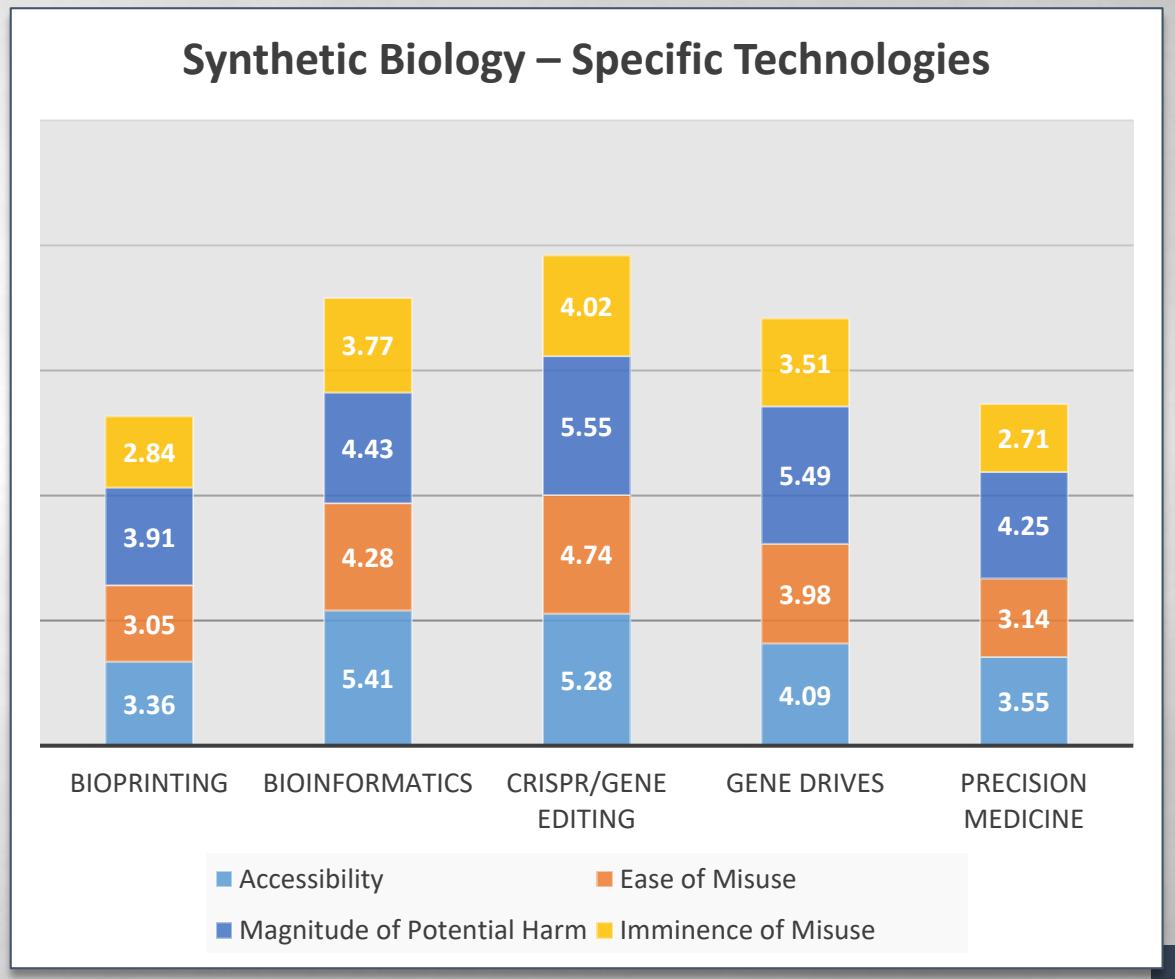
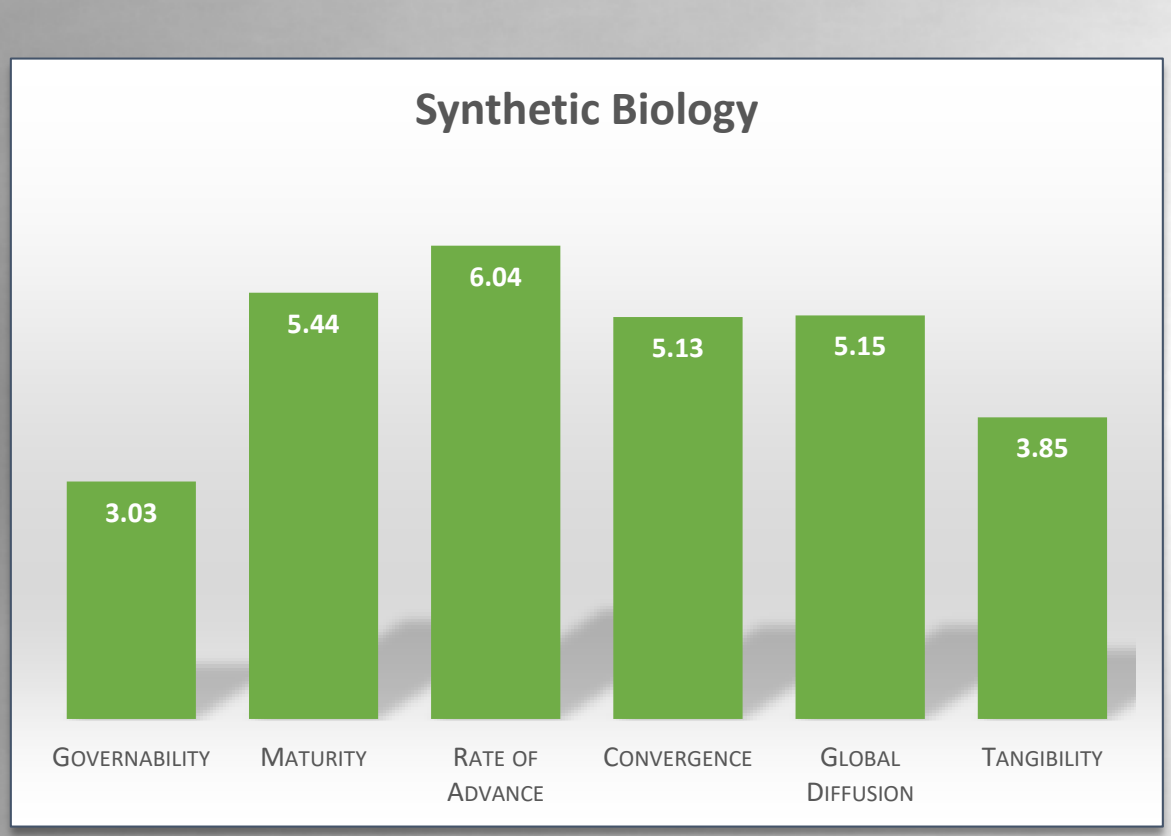
1.5 – 2.49	
2.5 – 3.49	
3.5 – 4.49	
4.5 – 5.49	
5.5 – 6.49	
6.5 – 7.0	

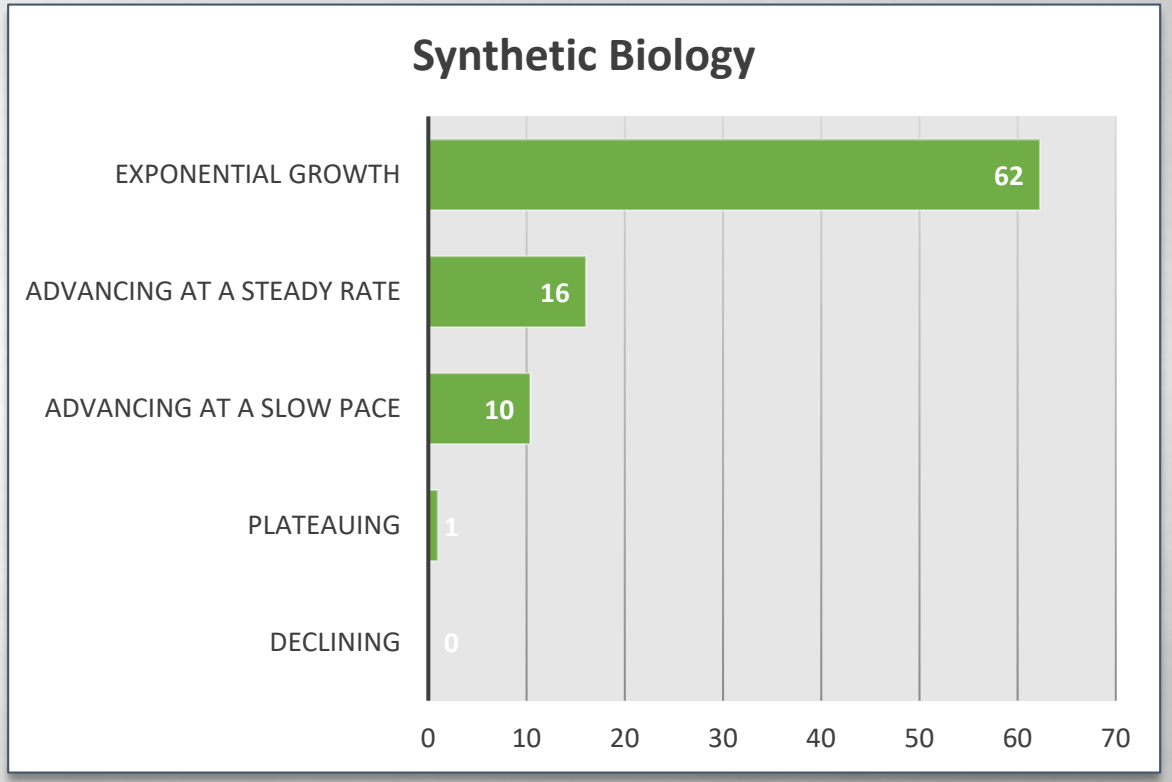
Risk of Misuse – SynBio



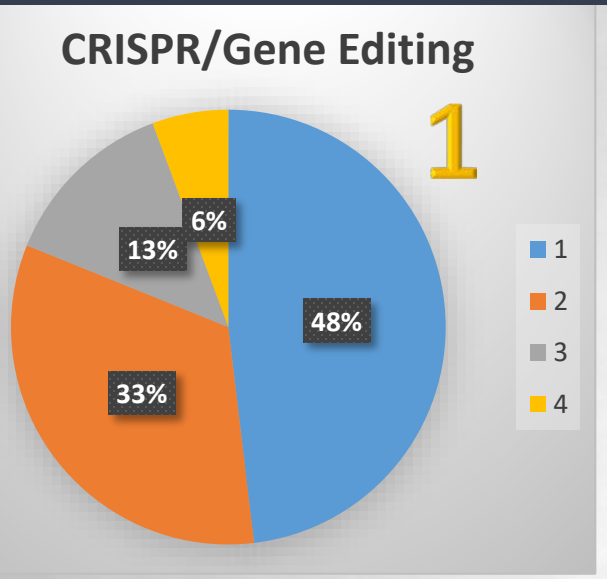


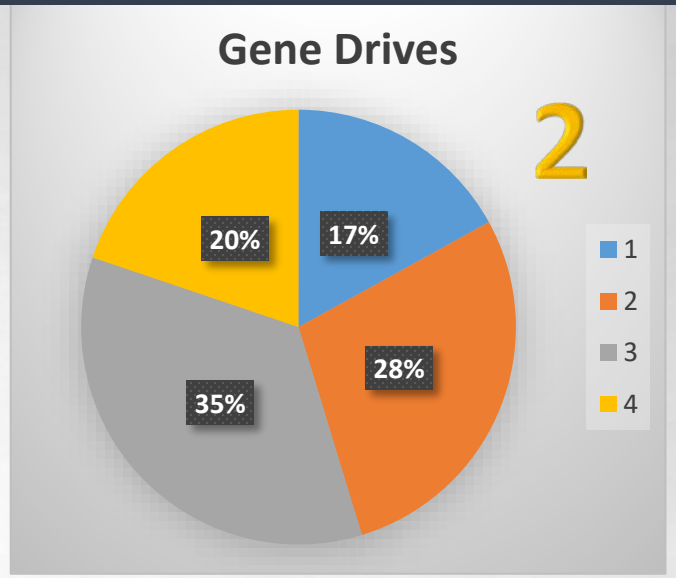
Governability – SynBio

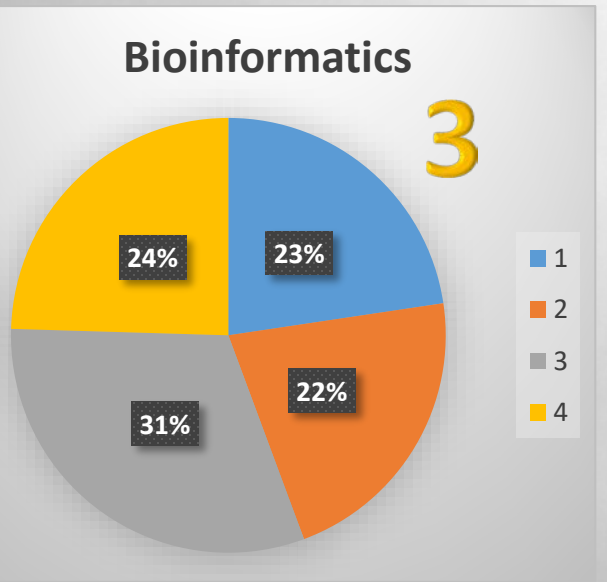


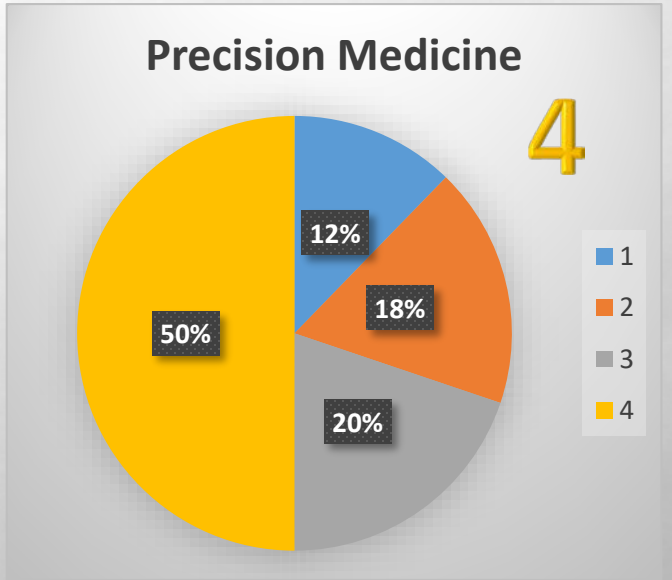


Ranked for Risk of Misuse - SynBio









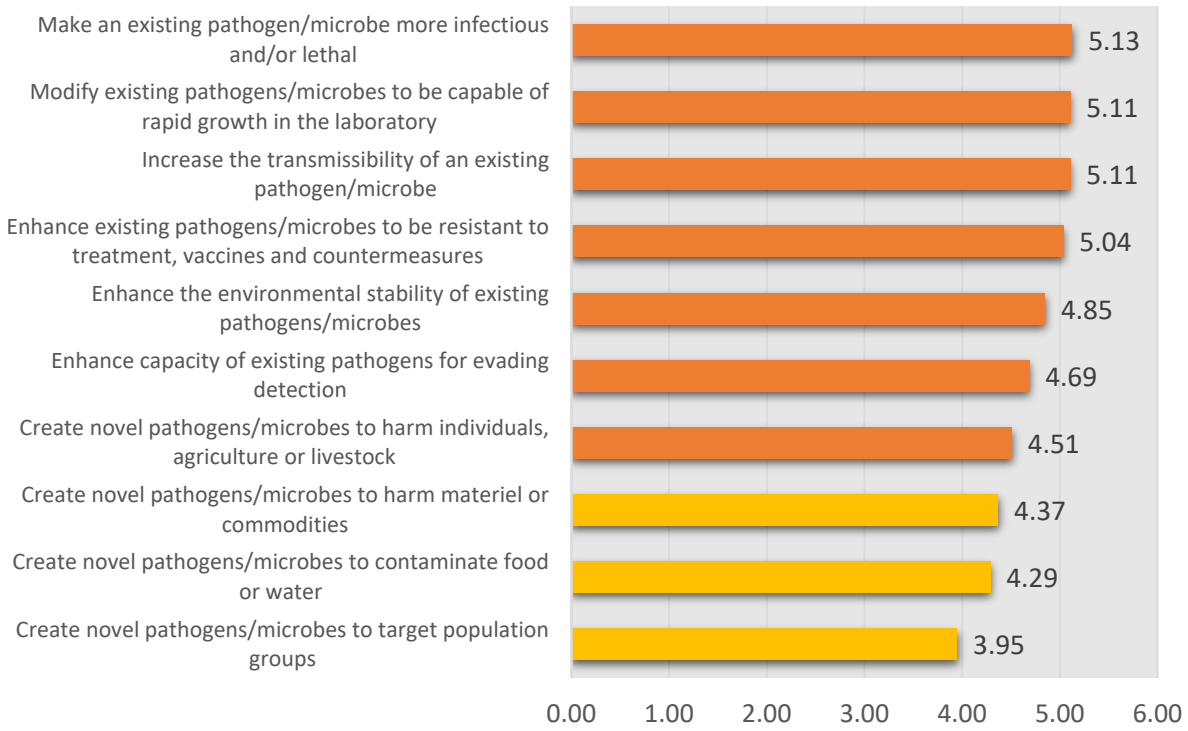
Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

WMD Pathways - SynBio

Center for the Study of WMD — Weapons of Mass Destruction

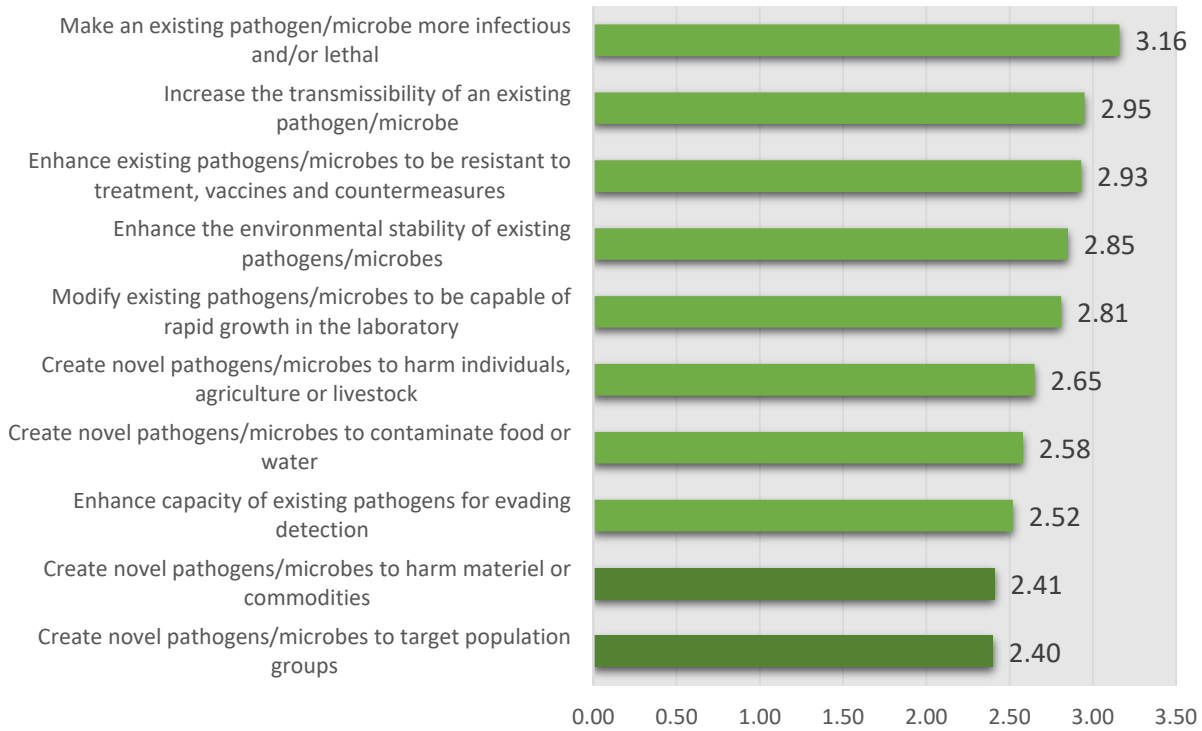
State Actors

Research and Development



Non-state Actors

Research and Development

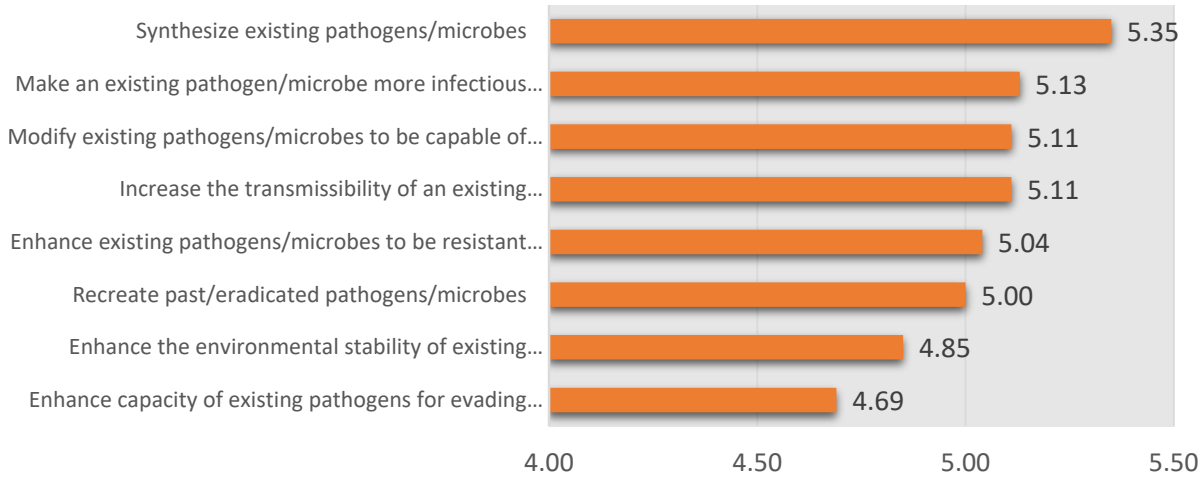


Risk	Color
Very Low	
Low	
Low-Medium	
Medium	
Medium-High	
High	
Very High	

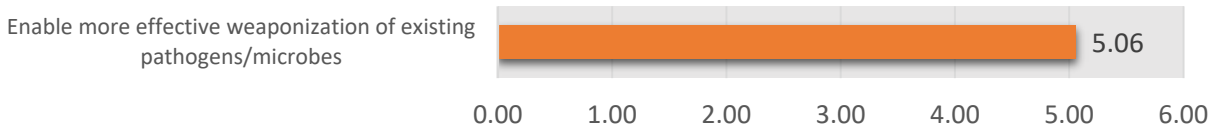
WMD Pathways - SynBio

State Actors

Acquisition and Production

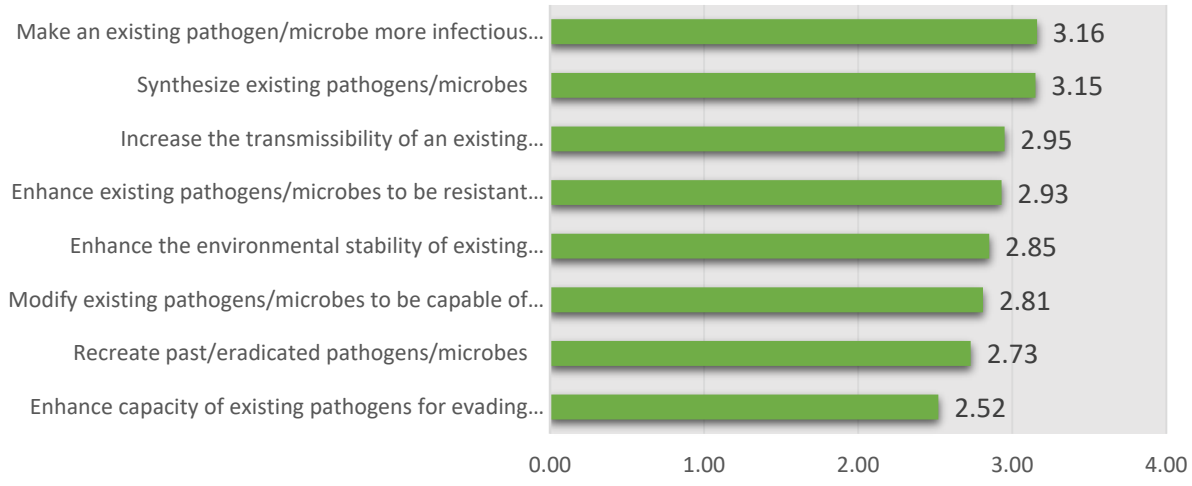


Weaponization and Delivery

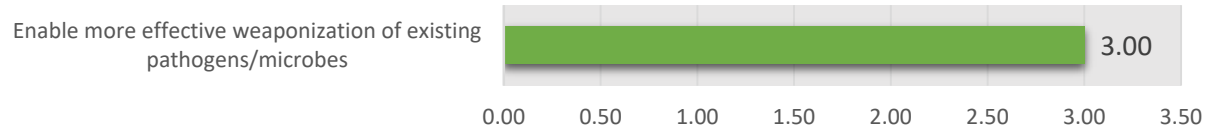


Non-state Actors

Acquisition and Production



Weaponization and Delivery



Other Enabling Effects – SynBio

Respondents suggested that we missed several enabling effects of synthetic biology for development or use of WMD

Research and Development:

- Development of molecular threat agents (nonliving, non-viral)
- Modify existing pathogens/microbes to change the host range (and/or to target selected subpopulations)

Acquisition and Production:

- Use of synthetic biology to enable industrial-scale toxin production

Final Conclusions

Risk versus Opportunity

- Emerging technologies are **primarily viewed through the "risk lens"** within the context of national security.
  - Due to the absence of metrics for evaluating "opportunity"
  - Sensitivity of efforts to enhance detection, countermeasures and response plans may be a factor
  - The emerging technologies in this survey are expected to enhance **detection, countermeasures, and response**; prevention is neglected by the technologies examined in this survey, but there is definitely promise elsewhere:
    - AI & machine learning
    - Blockchain
  - We are trained to think in terms of prevention for countering WMD (left of boom, left of loss, etc.)
- Should we put more emphasis on detection, countermeasures and response in the future?

State versus Non-State Actors

- State actors were consistently assessed higher scores than non-state actors
  - One negligible exception: Non-state actors (3.95) were assessed a slightly higher risk of misuse for synthetic biology than developing nation states (3.91)
  - The data results in the survey do not support current hype about non-state actors leveraging CRISPR to develop biological weapons
- Non-state actors were consistently assessed **low scores** across all technology groups
  - An important exception was the development of drones for use in terrorist operations and attacks
- Non-state actors are most likely to use **advanced robotics** and **additive manufacturing** to support the **weaponization and delivery stage** of their operations, but not necessarily for the delivery of WMD
- Non-state actors are least likely to use **nanotechnology**

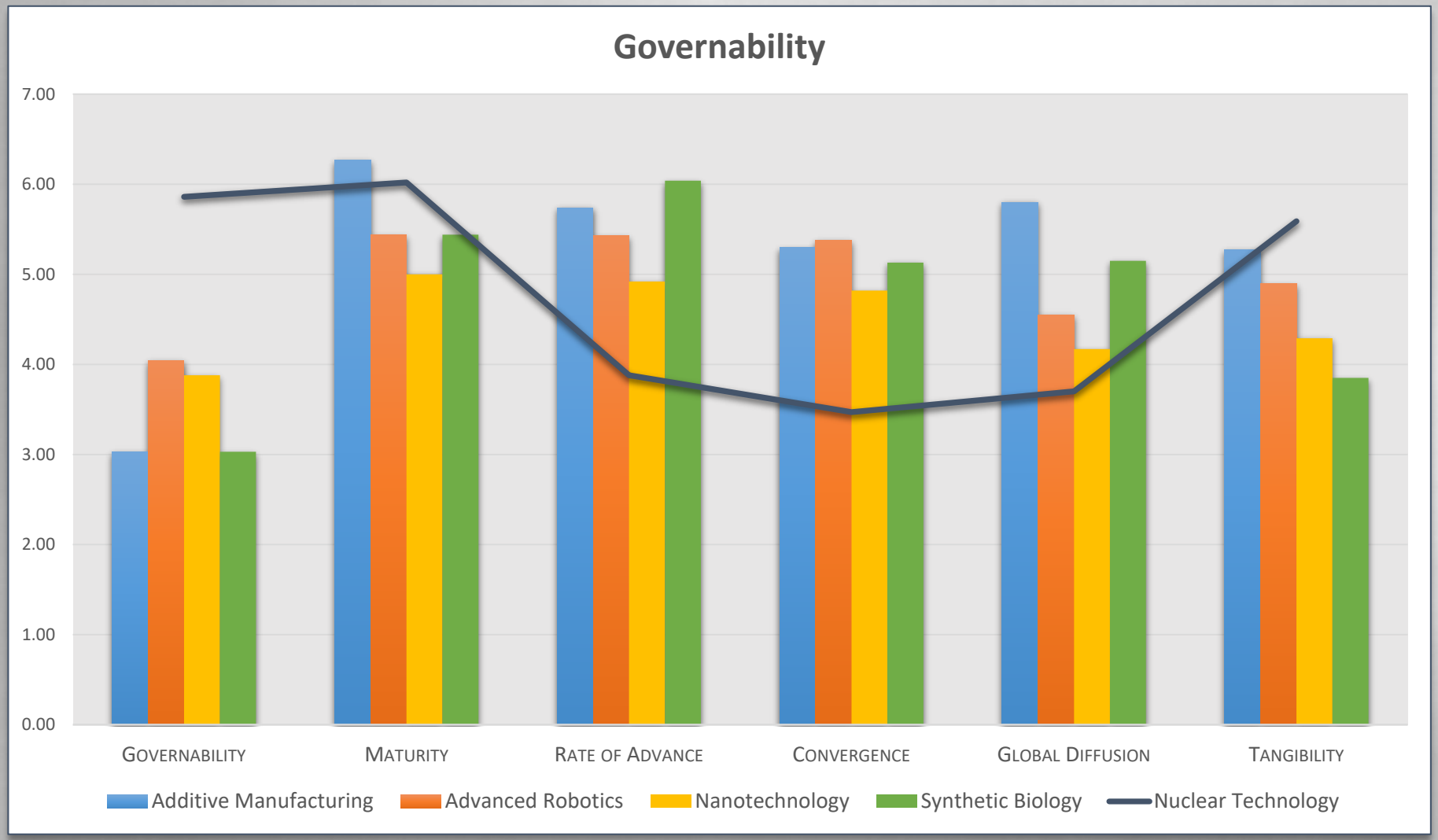
Direct versus Indirect Effects

- Emerging technologies **vary in their impact** on WMD development pathways
  - In the near-term, **additive manufacturing** and **nanotechnology** appear to have **indirect effects** at all stages of WMD development
  - In contrast, **synthetic biology** and **advanced robotics** appear to have more direct and focused effects
    - **Synthetic biology** appears to have greatest impact on **research and development** and R&D related efforts during the acquisition and production stage
    - **Advanced robotics** has impact on **weaponization and delivery** due to the high accessibility and ease of misuse of UAVs
- For technologies with direct effects, it will be easier to justify control measures to mitigate risks
  - Given their broad applicability and indirect impact on WMD, the risks of additive manufacturing and nanotechnology will be harder to control given a high opportunity cost

Old versus New Technologies

- **Nuclear technology** scores provided an interesting contrast to the emerging technologies in this study, confirming many of their key characteristics
  - Accessibility to a broader set of actors
  - Utility in a broader set of end-use applications
  - Ease of use and affordability
  - Digital character
  - Rapid advancement
  - High convergence with other emerging technologies
  - Global diffusion
- **Synthetic biology** and **nanotechnology** were assessed similar scores (somewhat higher) for magnitude of potential harm than nuclear technology

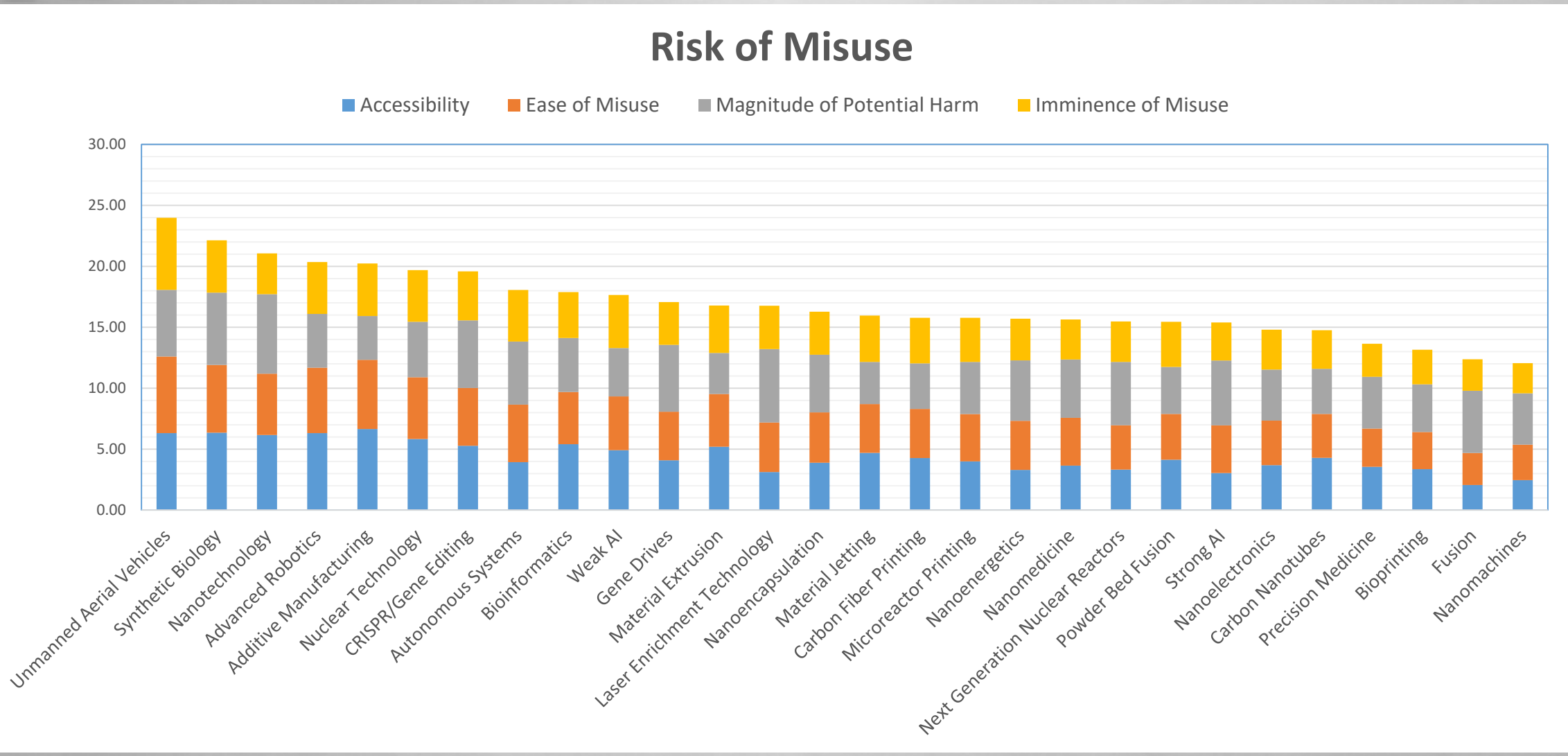
Old versus New Technologies



General versus Specific Technologies

- Assessed scores for the **technology groups as a whole** were higher than the scores for specific technologies
  - Potential factor: scores for technology groups were assessed separately for advanced states, developing states and non-state actors
  - Another factor: Much of the potential of emerging technologies remains untapped. SMEs may have accounted for this when assessing the technology group as a whole

General versus Specific Technologies



Other Emerging Technologies

Respondents suggested the following technologies (not covered in the survey) as having enabling effects for WMD:

- Advanced Computing/Quantum computing
- Big Data
- Dark Web for sharing/exchange of information
- Cyberwarfare
- Electromagnetic warfare/EMP
- High Power Microwave
- Lasers
- Geoengineering
- Cloaking
- Fermentation
- Aerosolization