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A NEW DIMENSION OF WAR: THE QUANTUM DOMAIN

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Exercise *Solo Flight*

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A NEW DIMENSION OF WAR: THE QUANTUM DOMAIN

Your past successes are your biggest obstacle: every battle, every war, is different, and you cannot assume that what worked before will work again.

– Robert Greene, *The 33 Strategies of War*

INTRODUCTION

For thousands of years war was fought on land because it was the main domain accessible to military forces. Research and development have progressively unlocked new domains and each time the character of war changed as opposing forces have sought to maximize these opportunities. Importantly, scientific discovery and technological achievement have led the way in opening new domains to humankind. This leads to a very important question — what domain will science unlock next?

This paper will examine current revolutions in scientific discovery and propose that the quantum domain will be the next accessible to warfare. This would provide the military with a sixth conceptual dimension within which to wage warfare when combined with the existing land, sea, air, space, and cyber domains. It would also demand specialized command and control arrangements to accommodate the fundamentally unique nature of the quantum domain. Ultimately, this paper will argue that the quantum domain is an arena within which the military could conduct future warfare in order to gain a potent strategic advantage over their adversaries.

To achieve the aim of this paper, the domains of warfare currently in use by militaries will be reviewed from a historical perspective in order to determine their origins and the contemporary definition of what constitutes a domain of warfare will be analyzed. Next, the

quantum domain will be considered in order to determine its validity as a domain of warfare. An alternate perspective will then be considered before a conclusion is delivered.

THE ORIGINS OF MODERN WARFARE DOMAINS

As a land-based species, humans have always inherently had the capacity to conduct land warfare. Agriculture and the State increased the scale of these endeavours through enhanced sustainment and organization; however, humans remained predominately confined to fighting their wars on the land.[1] It was scientific progress and technological achievement that progressively unlocked the sea, air, space, and cyber domains to warfare. This section will initially review the origins of each domain and then analyze the contemporary definitions of a domain of warfare.

In 1210 BC the first recorded sea battle occurred when Suppilumiuma II, King of the Hitties, commanded a fleet of ships against the Cypriots.[2] For the first time in recorded history, the sea domain had been used for warfare. Later in 1175 BC the Egyptian Pharaoh, Ramesses III, used combined land and naval forces to defeat a major sea invasion by the Sea People.[3] This joint military action demonstrated the ability of each domain to influence the other. However, all this would not have been possible without the prerequisite scientific discovery and technological development to build sea going vessels. It also took a visionary leader to recognize the sea could be used as a domain within which to conduct warfare and pursue military objectives.

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[1] Azar Gat, *War in Human Civilization* (New York NY: Oxford University Press, 2006), 159-160, 234.

[2] R Grant, *Battle at Sea: 3000 Years of Naval Warfare* (New York NY: DK Publishing, 2008), 23.

[3] G Beckman, "Hittie Chronology," *Akkadica 119-120* (2000): 22-23; Moshe Dothan. "Archaeological Evidence for Movement of the Early Sea Peoples in Canaan," in *Recent Excavations in Israel: Studies in Iron Age Archaeology*, ed. Seymour Gitin and William Dever (Winona Lake IN: Eisenbrauns, 1989), 67-68; Eric Marx, "The First Recorded Sea Battle," *The Mariners Mirror 32*, no. 4 (1946): 242-251.

In 206 BC, a General from the Han Dynasty used kites for signalling, measuring fortifications and scaring adversaries off the battlefield.[4] This pioneered the skies as a domain; although, it was 1903 before Orville Wright placed a human in the cockpit of a plane and made the first "powered, controlled, and sustained flight of a heavier-than-air machine."[5] The military slowly noticed and initially adopted manned aircraft in the Italian-Turkish War (1911-1912) and the First Balkan War (1912-1913). During these conflicts manned aircraft were employed to perform very basic reconnaissance tasks, artillery correction and bombing missions.[6] Once again, scientific discovery and technological development had led the way but it still took visionary leaders to exploit the potential on offer.

In 1957, the Soviet Union launched the first artificial satellite, Sputnik I, opening space as a domain.[7] In response, the USA combined their military missile knowledge and civilian space research to launch their own satellite, Explorer 1, on 31 January 1958.[8] The race for space dominance had begun and manned space flight became the next major milestone. The USSR won this race when they launched Yuri Gagarin into space on 12 April 1961; however, the USA quickly followed by launching Alan Shepard into space on 05 May 1961.[9] In the vast expanse of space, reaching the moon became the next target and the USA achieved this milestone on 20 July

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[4] Wendy Frey, John Bergez and Amy Joesph, *History Alive: The Ancient World* (Palo Alto CA: Teachers Curriculum Institute, 2004), 224; John Gray, *China: A History of the Laws, Manners and Customs of the People - Vol One* (London UK: Macmillan and Co, 1878), 269-270.

[5] World Digital Library, "Telegram from Orville Wright in Kitty Hawk, North Carolina, to His Father Announcing Four Successful Flights, 1903 December 17," last modified 22 September 2014, https://www.wdl.org/en/item/11372/.

[6] US Centennial of Flight Commission, "Aviation at the Start of the First World War," last accessed 18 February 2017, https://web.archive.org/web/20121009223955/http://www.centennialofflight .gov/essay/Air_Power/Pre_WWI/AP1.htm.

[7] US Department of State, *The Launch of Sputnik in 1957*, last accessed 03 May 2018, https://2001-2009.state.gov/r/pa/ho/time/lw/103729.htm.

[8] Central Intelligence Agency, "The Dawn of the Space Age," last accessed 19 February 2018, https://www.cia.gov/news-information/featured-story-archive/2007-featured-story-archive/the-dawn-of-the-space-age.html.

[9] National Aeronautics and Space Administration (NASA), "Yuri Gagarin: First Man in Space," last accessed 19 February 2018, https://www.nasa.gov/mission_pages /shuttle/sts1/gagarin_anniversary.html.

1969.[10] Once again, scientific discovery and technological development had unlocked a new domain and enabled its exploitation. Combined with visionary leadership, space allowed the USSR and USA to achieve important strategic victories over each other during the Cold War.

In 1981 the first known computer virus was spread via floppy disks.[11] In 1988, Robert Morris released the "Morris Worm" on the nascent internet. The worm exploited vulnerabilities to overload computers with invisible tasks and prevent their effective use.[12] This malicious activity established cyberspace as a potential domain yet it was not until 1996, when an Argentinean student was charged with illegally accessing US military computers, that the full potential of this domain became apparent.[13] By 2010 highly advanced cyber weapons that could cause physical destruction were being developed by technologically sophisticated nations. The most infamous of these was the Stuxnet Virus which destroyed Iranian nuclear enrichment centrifuges and was created at the behest of US Presidents Bush and Obama.[14] What is unique about cyberspace is that it was created entirely by humans; however, the inescapable truth remains that it was a product of scientific discovery and technological development. Furthermore, it took visionary leadership to realize the warfare potential of this domain.

This establishes the origins of the land, sea, air, space, and cyberspace domains and demonstrates that scientific discovery and technological achievement led the way in unlocking new domains of warfare. Each time a new warfighting domain became accessible it had been preceded by a breakthrough that made a unique environment accessible to humans. Interestingly,

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[10] National Aeronautics and Space Administration (NASA), "July 20, 1969: One Giant Leap for Mankind," last accessed 19 February 2018, https://www. nasa.gov/mission_pages/apollo/apollo11.html.

[11] Kamal Jabbour, "The Time Has Come for the Bachelor of Science in Cyber Engineering," *High Frontier: The Journal for Space and Cyberspace Professionals 6*, no. 4 (August 2010): 22.

[12] Gloria Wilt, "Making Information Safe," *Science & Technology Review* (January/February 1998): 5.

[13] *Ibid*., 7.

[14] David Sanger, "Obama Order Sped Up Wave of Cyberattacks Against Iran," last modified 01 June 2012, https://www.nytimes.com/2012/06/01/world/middleeast/obama-ordered-wave-of-cyberattacks-against-iran.html.

each foray into a new domain appears to have required the impetus of visionary leadership. This suggests that while science and technology may present opportunities, it takes ambitious and imaginative leaders to recognize and exploit the potential on offer.

THE DEFINITION OF A WARFARE DOMAIN

The seemingly simply question of what constitutes a domain of warfare is perhaps the hardest to answer. This section will review recent academic discussion surrounding the exclusion or inclusion of cyber as a domain. The debate in this area is both contemporary and enlightening when raising the proposition of adding a sixth, quantum domain to the dimensions of war already in existence. The most credible and vigorously cited academics include Chris McGuffin, Paul Mitchell, Scott Applegate and Daniel Kuehl; therefore, their published work will be considered as part of this discussion.

McGuffin and Mitchell argue that a domain of warfare must possess dimensional qualities that allow for an area of operations to be defined, have unique physical characteristics that shape the conduct of activity therein, be closely related to the concept of sovereign territory although not bound by it and have the capacity to project influence into other domains.[15] McGruffin and Mitchell state that this definition accommodates the land, sea, air and space domains but excludes the cyber domain. Their reservations will be explored further in the counter-argument later in this paper.

Applegate proposes a different way to define a warfighting domain which allows for the inclusion of a cyber domain. Applegate argues that the ability to maneuver in order to secure

[15] Chris McGuffin and Paul Mitchell, "On Domains: Cyber and the practice of Warfare," *International Journal 69*, no. 3 (September 2014): 402-404.

positional advantage that can be leveraged for decisive success defines the utility of a domain and that each domain has "its own set of unique characteristics and challenges and significantly overlaps operations in all four of the other warfighting domains."[16] For this reason, Applegate appears to suggest that a domain can be any sufficiently unique environment within which military manoeuvre can take place regardless of how artificial or abstract it may appear. This is underscored by his observation that "as technology has evolved and allowed for the expansion of warfare into new domains, so too has the concept of maneuver changed."[17] In essence, technology unlocks new and unique domains, which in turn changes the character of manoeuvre but not the nature of manoeuvre. Applegate concludes that his definition can accommodate all contemporary domains of warfare.[18]

Kuehl offers a third way to define a domain of warfare. He argues that two key criteria should be considered when determining the validity of a domain — distinct physical characteristics and the need for technology to exploit these characteristics.[19] Kuehl finds that each domain is distinguishable from another by its "radically different physical characteristics and they are usable only through the use of technology to exploit those characteristics."[20] He notes that ongoing technological progress throughout history has not only unlocked new domains, but enabled further exploitation of existing domains for military purposes.[21] Kuehl concludes that his definition can accommodate all five contemporary domains of warfare.

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[16] Chris Applegate, "The Principles of Maneuver in Cyber Operations," *4th International Conference on Cyber Conflict* (2012): 184.

[17] *Ibid*., 183.

[18] *Ibid*., 194.

[19] Daniel Kuehl, "From Cyberspace to Cyberpower: Defining the Problem," in *Cyberpower and National Security*, ed. Franklin Kramer, Stuart Starr and Larry Wentz (Lincoln NE: University of Nebraska Press, 2009), 24-25.

[20] *Ibid*., 24.

[21] *Ibid*., 24-25.

In summary, all four scholars agree that a domain must possess unique physical characteristics and that technological achievement enables the use of new domains. Even McGruffin and Mitchell find that "traditional domains of warfare evolved as technological innovations introduced new ways for people and nations to exert physical force against each other."[22] With this in mind, the quantum domain will now be examined to determine if it meets these commonly agreed upon criteria for being considered a warfighting domain.

THE QUANTUM DOMAIN

The quantum domain represents one of the truly final frontiers of science. It is a place that stumped even Albert Einstein and where many of the commonly taught laws of physics cease to be useful.[23] This is because classical physics is intended to explain matter and energy on a scale familiar to humans, whereas quantum mechanics generally studies particles at the atomic and subatomic levels.[24] This essay considers the quantum domain of warfare to be: a domain within the physical environment whose distinctive and unique character is framed by the use of quantum mechanics and technologies to generate quantum effects which exploit, alter or manipulate classical time, space and matter for a decisive warfighting advantage. The quantum domain starts where classical physics ends and Einstein's theories of relativity cease to be useful; although, its effects can be felt in all domains. This section of the essay will argue that the quantum domain possess highly unique physical characteristics. Furthermore, it will show that technology is increasingly opening the quantum domain to humankind.

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[22] Chris McGuffin and Paul Mitchell, "On Domains: Cyber and the practice of Warfare..., 410.

[23] Abraham Pais, *The Science and Life of Albert Einstein* (New York NY: Oxford University Press, 2005), 443; A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" Physical Review 47, no. 10 (May 1935): 777-780.

[24] Corey Powell, "Relativity vs Quantum Mechanics," last modified 04 November 2015, https://www.theguardian.com/news/2015/nov/04/relativity-quantum-mechanics-universe-physicists.

A Unique Domain

The quantum domain is unique and counterintuitive because it challenges the seemingly objective reality to which much of humankind has become accustomed. The best examples of this can be found in quantum experiments that directly challenge our understanding of physical matter, time and space. Take light for example — in the quantum domain a photon of light can exist as both a particle and a wave.[25] This is known as wave-particle duality.[26] The double slit test offers an empirically repeatable experiment for observing this phenomenon. By firing individual photons through a two-slit barrier and onto a screen a wave pattern will be generated. To form a wave pattern each individual photon must simultaneously travel through both slits, along every possible pathway and interfere with these other versions of itself.[27] This is possible because within the quantum domain particles are inherently uncertain, probabilistic in nature and subject to superposition.[28] However, any form of direct observation collapses the wave function and causes the individually fired photons to behave as particles.[29] This collapse can be triggered by placing a photon detector at the barrier slits. Such observation causes each photon to choose a definite path earlier and results in a particle pattern on the final screen. The very act of measuring a photon of light changes how it behaves.[30] This experiment has since been successfully repeated

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[25] Kelly Dickerson,"Scientists take the first ever photograph of light as both a wave and a particle," last modified 02 March 2015, http://www.businessinsider.com/image-of-light-as-a-wave-and-a-particle-2015-3; L. Piazza et al, "Simultaneous observation of the quantization and the interference pattern of a plasmonic near-field," *Nature Communications 6* (March 2015): 6407-6419.

[26] Robert Eisberg and Robert Resnick, *Quantum Physics: Atoms, Molecules, Solids, Nuclei and Particles* (Hoboken NJ: John Wiley and Sons, 1985), 62-65.

[27] Johan Prins, "Causality and Reality in Quantum Physics," last modified 24 July 2006, https://arxiv.org/abs/physics/0607209, 23-24.

[28] Robert Eisberg and Robert Resnick, *Quantum Physics*..., 62-69.

[29] *Ibid*., 24.

[30] Sacha Kocsis et al, "Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer," *Science 332*, no. 6034 (03 June 2011): 1170-1173; University of Toronto, "Quantum physics first: Researchers observe single photons in two-slit interferometer experiment," last modified 02 June 2011, https://phys.org/news/2011-06-quantum-physics-photons-two-slit-interferometer.html.

with larger particles and more classical matter — electrons, atoms and even molecules.[31] In essence, physical matter within the quantum domain can assume properties that are unique from all other warfighting domains.

Leveraging the effects described above, scientists have developed other experiments that seemingly reach back in time and further illustrate the unique characteristics of the quantum domain. By reflecting photons off a satellite which allows two pathways to be taken back to earth, and then choosing a measurement apparatus while the photons are travelling back to earth, scientists demonstrated they could retroactively alter the path a photon must have taken at the satellite.[32] This does not technically violate time, but it does defy the commonly understood notion of causality by reversing cause and effect. The implications of this are significant, as observed by the physicists George Ellis and Tony Rothman:

> The nature of the future is completely different from the nature of the past. When quantum effects are significant, the future shows all the signs of quantum weirdness, including duality, uncertainty, and entanglement. With the passage of time, after the time-irreversible process of state-vector reduction has taken place, the past emerges, with the previous quantum uncertainty replaced by the classical certainty of definite particle identities and states. The present time is where this transition largely takes place, but the process does not take place uniformly: *Evidence from delayed choice and related experiments shows that isolated patches*

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[31] Joseph Cotter et al, "In search of multipath interference using large molecules," *Science Advances 3*, no. 8 (11 August 2017): 1-6; S. Eibenberger et al, "Matter-wave interference of particles selected from a molecular library with masses exceeding 10,000 amu," *Physical Chemistry Chemical Physics 15*, no. 35 (21 September 2013): 14696-14700.

[32] Francesco Vedovato et al, "Extending Wheeler's Delayed-Choice Experiment to Space," *Science Advances 3*, no. 10 (25 October 2017): 1; Adrian Cho, " Quantum experiment in space confirms that reality is what you make it," last modified 27 October 2017, http://www.sciencemag.org/news/2017/10/quantum-experiment-space-confirms-reality-what-you-make-it-0.

> *of quantum indeterminacy remain, and that their transition from probability to certainty only takes place later* [emphasis added].[33]

In essence, the unique nature of the quantum domain allows decisions regarding the path and state of particles to be delayed until longer than the classically understood notion of causality would allow. This is fundamentally different from all other warfighting domains.

Quantum tunnelling and quantum entanglement offer further evidence of unique physical characteristics that are only observed within the quantum domain. Quantum tunnelling is a phenomenon whereby a particle tunnels through a barrier that classical physics would not otherwise allow.[34] This occurs due to the uncertain and probabilistic nature of particles within the quantum domain when in a wave state.[35] Quantum entanglement is another phenomenon whereby paired or grouped particles are inextricably linked and to measure one particle instantaneously collapses the wave function of all other entangled particles. This occurs regardless of how much distance separates the paired or grouped particles and happens faster than the speed of light. Seemingly, every entangled particle instantly "knows" when another has been measured and assumes a complementary non-wave like state of being. This experiment has now been successfully performed with photons, electrons, molecules and even small diamonds.[36]

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[33] George Ellis and Tony Rothman, "Time and Spacetime: The Crystallizing Block Universe," *International Journal of Theoretical Physics 49*, no. 5 (May 2010): 988.

[34] S. McKagan, K. Perkins and C. Wieman "Quantum Mechanics: The Case of Tunnelling." *Physical Review: Physics Education and Research 4*, no. 2 (July-December 2008): 1-2.

[35] *Ibid*., 2; Razavy Mohsen, *Quantum Theory of Tunnelling: 2nd Edition* (Singapore: World Scientific, 2013), 1-5.

[36] P. Kwiat et al, "New High-Intensity Source of Polarization-Entangled Photon Pairs," *Physical Review Letters 75*, no. 24 (11 December 1995): 4337–4341; J. Formaggio et al, "Violation of the Leggett-Garg Inequality in Neutrino Oscillations, "*Physical Review Letters 117*, no. 5 (26 July 2016): 050402; B. Hensen et al, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres," *Nature 526*, no. 7575 (29 October 2015): 682-686; K. Lee et al, "Entangling Macroscopic Diamonds at Room Temperature," *Science 334*, no. 6060 (02 December 2011): 1253-1256.

In summary, the quantum domain has highly unique physical characteristics. This is most evident through research and experiments into quantum entanglement, quantum tunnelling, wave-particle duality, delayed choice and retroactive causality. These phenomena challenge the fundamental understanding of time, space and matter that is taken for granted in all other warfighting domains. For this reason, the quantum domain is assessed to have sufficiently unique physical characteristics to warrant domain status.

Quantum Technology

Technology is increasingly opening the quantum domain to use by humankind. This offers profound opportunities to the military which are tentatively being explored. This most significant of these include quantum encryption, radar, sensors and computers.

In 2016 China launched a quantum communications satellite into space that relies upon entangled photons to produce encrypted communications that are unprecedentedly secure and cannot be eavesdropped upon without detection.[37] China intends to launch 20 more to establish a completely secure network.[38] Quantum radar systems that make use of entangled particles to detect stealth aircraft are also being developed by China, Britain and the USA.[39] Quantum sensors that can determine positional data with unprecedented accuracy, independently of global

[37] Elizabeth Gibney, "One giant step for quantum internet," *Nature 535*, no. 7613 (28 Jul 2016): 478; Philip Ball, "Intercontinental, Quantum-Encrypted Messaging and Video," *Physics 11*, no. 7 (19 January 2018): 1-2.

[38] *Ibid*., 479.

[39] Philip Ball, "Quantum Mechanics Could Improve Radar," *Physics 8*, no. 18 (27 February 2015): 1; Stephen Chen, "The end of stealth? New radar capable of detecting 'invisible' targets 100km away," last modified 12 June 2017, http://www.scmp.com/news/china/article/2021235/end-stealth-new-chinese-radar-capable-detecting-invisible-targets-100km; Seth Lloyd, "Enhanced Sensitivity of Photodetection via Quantum Illumination," *Science 321*, no. 5895 (12 September 2008): 1463-1465: Lockheed Martin, "Patent for radar systems and methods using entangled quantum particles," last accessed 06 May 2018, https://patents.google.com/patent/US7375802B2/en.

positioning satellites, are another technology under development.[40] Finally, quantum computers that use superposition and entanglement to process vast amounts of data simultaneously offer incredible potential.[41] Lockheed Martin claim their experimental quantum computer can "sort through tremendous possibilities — more variables than all of the digital data created in an entire year — in 10 nanoseconds."[42] Furthermore, the military needs to be an active participant in the quantum domain or risk having discoveries with weapons potential concealed from them.[43]

These technologies all serve to demonstrate how technological achievement is increasingly enabling the quantum domain to be exploited by humanity. Combined with the unique physical characteristics of the quantum realm, it becomes increasingly evident that the establishment of a quantum domain of warfare bears serious consideration.

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[40] Andreas Wicht, Markus Krutzik and Andreas Thoss, "Quantum Technology: Quantum sensing is gaining (s)pace," last modified 18 January 2018, https://www.laserfocusworld.com/articles/print/volume-54/issue-01/features/quantum-technology-quantum-sensing-is-gaining-s-pace.html; V. Gerginov, F.C.S. da Silva and D. Howe, "Prospects for magnetic field communications and location using quantum sensors," *Review of Scientific Instruments 88* (2017) cited by US Department of Commerce, last modified 02 January 2017, https://www.nist.gov/news-events/news/2018/01/quantum-radio-may-aid-communications-and-mapping-indoors-underground-and.

[41] University of Waterloo: Quantum Computing Institute, "Quantum Computing 101," last accessed 06 May 2018, https://uwaterloo.ca/institute-for-quantum-computing/quantum-computing-101.

[42] Lockheed and Martin, "Enter the Universe of Quantum Computing," last accessed 06 May 2018, https://web.archive.org/web/20171022131857/https://www.lockheedmartin.com/us/news/features/2013/ipad-quantum.html.

[43] Bob Yirka, "Theoretical quark fusion found to be more powerful than hydrogen fusion," last modified 06 November 2017, https://phys.org/news/2017-11-theoretical-quark-fusion-powerful-hydrogen.html; Marek Karliner and Jonathan Rosner, "Quark-level analogue of nuclear fusion with doubly heavy baryons," *Nature 551*, no. 7678 (November 2017): 89-91.

AN ALTERNATE PERSPECTIVE

McGuffin and Mitchell excluded cyberspace from domain status on the basis of key technical, procedural and physical differences.[44] These may also serve to exclude the quantum environment from domain status and warrant further consideration.

First, the technical difference between cyberspace and all other domains is that it is an impermanent human creation that is volatile and can be fundamentally altered.[45] The quantum domain does not suffer from this shortcoming as it is a naturally occurring aspect of the physical world which obeys quantifiable laws of physics, even if they are poorly understood or counterintuitive when compared to classical physics.

Second, McGuffin and Mitchell identified a key technical distinction between cyberspace and physical domains whereby cyber weapons could be mitigated or nullified as soon as recognized.[46] By contrast, quantum mechanics and their effects cannot be countered or eliminated in the same way cyber vulnerabilities can be updated or patched. Quantum tunneling, entanglement, delayed choice and wave-particle duality are unique yet natural phenomena that will still exist regardless of human intervention.

Finally, McGuffin and Mitchell found cyberspace differed from other domains on a physical basis in that it is impossible to fully control, lacks clear boundaries and cannot be entered by humans.[47] Admittedly, the quantum domain does share some of these shortcomings. Since the quantum domain generally relates to particles at the atomic and subatomic levels, it cannot be occupied by humans. However, it could be argued that unmanned platforms (be they

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[44] Chris McGuffin and Paul Mitchell, On Domains: Cyber and the practice of Warfare..., 408.
[45] *Ibid*., 408.
[46] Chris McGuffin and Paul Mitchell, On Domains: Cyber and the practice of Warfare..., 409.
[47] *Ibid*., 404, 409.

kites or drones) do not negate the domain status of physical environments, nor would they if they were to assume ascendancy over manned platforms. Additionally, defining full control and clear boundaries in the quantum domain would be very difficult. Arguably, full control could never be established because of the unique nature of the quantum domain which challenges the classical understanding of physical matter, time and space. Furthermore, clear boundaries for the domain are lacking because science is still attempting to reconcile classical and quantum physics under a single unified theory.

In summary, the quantum domain only partially meets the criteria established by McGuffin and Mitchell for domain status because it lacks physical elements these academics believe are important. Critically, it is exactly these kinds of unique physical characteristics that one could argue make the quantum domain distinct from the other physical domains and worthy of domain status.

CONCLUSION

The quantum domain should be considered a domain of warfare. Having reviewed the historical origins of existing warfighting domains it is evident that scientific discovery and technological development ultimately unlock new domains. Analysis of recent debate regarding the inclusion of cyber as a domain has identified two essential criteria for domain status — unique physical characteristics and technological achievement sufficient to enable the domain to be used. The quantum domain possesses both these attributes. It has unique physical characteristics that are evident through phenomena such as quantum entanglement, quantum tunnelling, wave-particle duality, delayed choice and retroactive causality. Recent technological

advances are also opening this domain to humanity via quantum encryption, radar, sensors and computers.

Critics who argue against cyberspace as a domain would no doubt object to the creation of a quantum warfighting domain, most likely on the basis that it lacks important physical criteria. In response, it is proposed that precisely these kinds of physical differences are what make the quantum domain physical distinct from all other warfighting domains.

Importantly, one key ingredient is lacking when it comes to establishing a quantum domain of warfare — visionary leadership. The current use of quantum effects by new technology is largely evolutionary and consistent with conventional military operations, notions of causality and objective reality. In order to exploit the untapped potential of the quantum domain a revolution in military affairs is required. The profound anomalies, unique characteristics and counterintuitive nature of the quantum domain must be fully embraced if the potential on offer is to be realized. In essence, the military needs to follow science deeper into the quantum domain or risk falling behind potential adversaries. This demands visionary leadership and the elevation of the quantum realm to the formal status of a warfighting domain.

Finally, this essay has identified an area of ongoing investigation due to its potential for military applications. Experiments regarding quantum wave-particle duality and quantum entanglement have progressively demonstrated these phenomena can be repeated with larger and larger particles of matter.[48] However, the upper size limit of matter that can be subjected to these quantum effects remains undetermined. This warrants further study and continuous observation of scientific breakthroughs as they occur in these particular areas of quantum physics.

[48] Joseph Cotter et al, In search of multipath interference..., 1-6; S. Eibenberger et al, Matter-wave interference of particles..., 14696-14700; P. Kwiat et al, New High-Intensity..., 4337–4341; J. Formaggio et al, "Violation of the Leggett-Garg Inequality..., 050402; B. Hensen et al, Loophole-free Bell inequality violation ..., 682-686; K. Lee et al, Entangling Macroscopic Diamonds..., 1253-1256.

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