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Introduction: A technology management and innovation systems perspective on ARPA

To understand DARPA, it is important to understand its contribution to a critical phase in the emergence of a new technology. DARPA is especially effective in the phase of a technology lifecycle when exploration and exploitation endeavours are strongly connected; when early engineering efforts have begun, but significant scientific discovery continues, promising significat further performance improvements.

DARPA is too often characterised *solely* in terms of its distinctive (non-technical) operational features: its mission-driven focus on high risk/high reward research; its low levels of bureaucratic 'red tape'; and its empowered and visionary program managers. While these qualities are essential in enabling DARPA to function so effectively, they do not capture what is distinctive about DARPA's technical functions – the genius in the details of how DARPA actually manages technological innovation.

DARPA is not a research organisation: It does not own its own labs or facilities. DARPA is a *programme management* agency, supporting carefully designed portfolios of R&D projects, focused on disruptive emerging technologies, driven by a programme manager's vision, and carried out by the best teams selected directly by the programme manager (PM).

This programme approach allows DARPA perform an important function at the interface of technology exploration and exploitation, in particular: coherently nurturing the linkages and configuration of emerging technology R&D networks; removing bottlenecks (and 'frictions') within evolving innovation systems; and gradually revealing and catalysing emerging technology development pathways.

Without understanding *when* and *how* DARPA impacts emerging technology lifecycles, it is not possible to understand key issues critical to the design of UK-ARPA:

- What types of R&D challenge are *ARPA-able*
- How the ARPA *programme* approach effects changes in the research & innovation system

This note offers a technology innovation management perspective on the ARPA model, addressing the following questions:

- When and how does ARPA impact emerging technology lifecycles?
- How does ARPA address 'market failures' and 'frictions' in innovation system?
- How does ARPA build 'connected science' R&D networks?
- How does ARPA design (and refine) technology challenge visions and R&D programmes?
- What capabilities and expertise make ARPA Programme Managers (PMs) effective?
- Why are 'missions' and low bureaucracy essential for effective ARPA programme management?

The note concludes by reflecting on the implications for the UK Research & Innovation system and the Inquiry questions related to nature and purpose of the new UK agency.

When and *how* does ARPA impact technology lifecycles?

DARPA plays a crucial role at a particular stage of an emerging technology's lifecycle when the exploration and exploitation phases are strongly coupled, catalysing disruptive advances in tech performance. This is the phase when early engineering efforts have begun, but significant scientific discovery continues and promises significant potential for performance improvements. The functionality of the new technology – the scientific principles underpinning its behaviour, the limits of its performance - are still being explored. But so too, increasingly, are the opportunities for application and the development pathways to its exploitation [Azoulay, 2018].

The DARPA programme approach, funding portfolios of projects related to both exploration and exploitation are better placed to navigate this stage in the technology lifecycle – bridging the gap between basic and applied research. During this phase, the innovation process can be supported by bring a connectedness and coherence to exploration and exploitation endeavours: Ensuring early technology development efforts are informed, refocused, and refined by the latest scientific progress; and ensuring use-inspired basic research efforts are informed, refocused and refined based on the latest technology demonstration results.

The ARPA model is particularly adept at managing the innovation process as technological performance principles become clearer, as new innovation system configure around emerging opportunities, and as the technology development pathways become more focused.

How does ARPA tackle 'market failures' and 'frictions' in innovation system?

DARPA supports emerging technology R&D during a phase when there are very many sources of innovation system uncertainty. Not only are there uncertainties related to technology feasibility, application viability and manufacturability, but also related to the disruption of established engineering methods, tools, and industrial practices. Furthermore, there are challenges in efficiently translating new knowledge back-and-forth through fragmented, embryonic networks of research, development, demonstration and deployment activities.

These market failures mean that individual firms are inhibited from investing in R&D because of the sheer variety of innovation system uncertainties and "*frictions in the pathways through development, demonstration, and broad-scale deployment*" [Azoulay, 2018]. And the consequent risks to firms of not capturing the value from their innovation efforts. The ARPA model seems particularly effective in catalysing disruptive technology development under these conditions.

In particular, DARPA programmes address these innovation system challenges and 'frictions' through a process that the leading US ARPA expert, Prof William Bonvillian has dubbed '*connected science*' [Bonvillian, 2009] In this approach, more fundamtental scientific discovery endeavours are proactively connected to the follow-on innovation stages related to development. Breakthroughs from more fundamental research activities inform technology development efforts; insights from technology demonstration endeavours inform use-informed basic research.

How DARPA builds 'connected science' R&D networks

While DARPA programme staff do not carry out research themselves, they play a key role in building the 'connected science' R&D networks that do. Programme managers proactively nurture new R&D networks, bringing together a range of scientific and engineering expertise from universities, research institutes and R&D-intensive technology firms. This process starts to fill in missing capabilities in the emerging innovation system – linking competences and resources associated with scientific discovery, technology R&D, application R&D, research and engineering tool development, demonstration of manufacturability and scale-up.

In particular, these DARPA research programme communities of connected researchers and technical experts allow for more effective knowledge exchange and information flows [Fuchs, 2010]. This, in turn, leads to enhanced awareness, reduced information asymmetries and coherence along the innovation pathway from research, development, demonstration, and deployment.

In this context, a critical role of the DARPA PM is to identify the R&D actors with the best ideas and capabilities to address important challenge goals associated with the programme vision. In doing so DARPA builds research collaborations, R&D networks and industrial-innovation communities that persist beyond the programme itself, and become a source of ongoing competitive advantage in the new technology domain.

How does DARPA design (and refine) programmes?

However brilliant and visionary individual ARPA programme managers are, the process of programme design and management is not done in isolation, but involves ongoing engagement with the innovation community to develop a 'vision' for disruptive technology solutions; and to design (and refine) the research programme challenge goals to achieve that vision.

Programme managers work closely with military strategists (to understand mission priorities and requirements), the research community (to brainstorm emerging technology opportunities), and with industrial experts (to identify potential technology development pathways and bottlenecks). This process can occur through formal working groups or informal brainstorming meetings. Project teams are selected by the Programme Manager (*not* peer review) based on their vision and judgement regarding which groups are best placed to tackle specific challenge goals.

The programme priorities and goals are continuously refined and focused. Findings from demonstrators and testbeds generate new insights into innovation barriers, performance improvements and application opportunities. These are presented at programme events and brainstorming workshops to further refine and focus the vision and stretch goals. These technical and community feedback cycle allows DARPA to increasingly focus their visions to reveal the most promising technology development pathways [Carleton, 2019].

What capabilities make Programme Managers effective? And where do PMs come from?

The role of the DARPA programme manager in building R&D networks and catalysing technology development pathways has significant implications for what technical expertise and management capabilities they require.

Given the PM's role in building social networks of technologists and innovators, there is value in a career history which provides an awareness of the broader research community. An awareness which allows the PM to convene the right expert workshops assemble the right project research teams, but also appreciate the different capabilities, incentives, and constraints of teams from different academic or industry backgrounds.

Similarly, given the PM's role in targeting nascent technology development pathways, there is value in a career experience that allows them to anticipate sources of innovation risk and develop mitigation strategies and demonstration priorities. In particular, there is value in accumulated insights and expertise related to *both* technology exploration *and* exploitation. Evidence from academic literature, and policy studies, suggests that many ARPA PMs have academic *and* commercial career experience, often with expertise across multiple stages of technology research, development, demonstration and deployment [NASEM, 2017; Bonvillian, 2011].

Why are 'missions' and low bureaucracy so important?

From a technology management perspective, missions are a valuable focusing mechanism that supports a coherence of innovation effort at a key phase in an emerging technology lifecycle. Missions and 'moonshots' can bring a coherence of vision to an otherwise disparate community of science researchers, technology engineers and application developers. They can also give a mandate to engage across the interface between exploration and exploitation. And give license to address a variety of "frictions" in the innovation system. A mission can be an invaluable focusing mechanism but is not sufficient condition for programme impact: 'Moonshot' goals without a coherent vision, or the wherewithal to nurture new innovation communities, or effective linkages along the research, development and demonstration lifecycle are unlikely to succeed.

DARPA's approach to innovation management - involving empowered visionary Programme Managers, project team selection based on the PM's judgement, and funding prototypes and demonstrators – means that flexibility and responsiveness are critical [Azoulay, 2018; Bonvillian, 2011; Fuchs, 2010]. In particular, in order for ARPA to hire the visionary PMs they need, quickly and with more competitive salaries, it may be necessary to hire outside of normal civil service regulations. Similarly, because PMs directly select research teams with the specific capabilities and resources required by the programme vision (rather than more general domain expertise), there may need to be greater flexibility around funding guidelines. Similarly, in order to fund prototypes and testbeds, addressing specific demonstration goals, it may be important to have flexible contracting procedures outside conventional governmental procurement rules.

Implications for the UK

To understand the DARPA model - and how it might be adopted (and adapted) in the UK - it is important to understand *when* and *how* DARPA impacts emerging technology lifecycles. In summary:

- DARPA is especially effective in the phase of a technology lifecycle when exploration and exploitation endeavours are strongly connected; when early engineering efforts have begun, but significant scientific discovery continues, promising further performance improvements.
- DARPA is a *programme management* agency (it does not own its own labs or carry out its own research) supporting portfolios of R&D projects, focused on disruptive technologies, driven by a programme manager's vision, and carried out by teams selected directly by the programme manager.
- DARPA impacts disruptive technology lifecycles by coherently nurturing emerging technology R&D networks; removing bottlenecks within evolving innovation systems; and gradually revealing and catalysing promising technology development pathways.

In this context of this technology innovation management perspective, the following section reflects on some of the Inquiry questions related to nature and purpose of *A New UK Research Funding Agency*:

- **What gaps in the current UK research and development system might be addressed by an ARPA style approach?**
  The ARPA model could fill an important gap at the interface between technology exploration and exploitation efforts, providing a mechanism to nurture nascent emerging technology R&D networks and catalyse novel technology development pathways.

  This role is one that cannot be easily addressed by the Research Councils or Innovate UK, which have more singular organisational missions and structures focused on exploration and exploitation, with different funding criteria, objectives and communities.

  In particular, an ARPA model could address emerging 'disruptive' technology domains, where the degree of disruption requires the development of new innovation networks, R&D tools and infrastructure. In this context, the mission-led *programme* approach (involving portfolios of projects) brings a coherence and focus on "pathways to implementation" which can facilitate system change.

- **What are the implications of the new funding agency for existing funding bodies and their approach?**
  If UK-ARPA follows the US model (and does not carry out its own research), then projects will be carried out by external teams. These teams are likely to be groups that that existing agencies have funded, and may use facilities that the agencies have invested in. This will mean new competition for the finite research bandwidth and facilities of the most talented researchers.

  ARPA Programmes are developed based on insights from the broader R&I community. Awareness of other agencies' insights (e.g. regarding research breakthroughs, commercialisation challenges, new facilities) will be important to the success of UK-ARPA. New mechanisms for interagency information exchange may be needed.

  There may be a need to examine how existing promotion and assessment processes could create barriers to academic researchers participating in UK-ARPA programmes (or becoming UK-ARPA PMs). For example, projects may not generate outputs appropriate for the *Research Excellence Framework*. Or there may be career risks in working on ARPA projects which can be shut down by PMs (if alternative projects, exploring competing approaches, deliver more promising results).

- **What should be the focus be of the new research funding agency and how should it be structured?**
  The new agency should focus on technology challenges which are ARPA-able, i.e. which have some or all of the following features:
    - **Be at the interface of technology exploration and exploitation:** Challenges at the phase in a technology lifecycle where exploratory research has potential to offer major performance improvements to emerging technology engineering / exploitation endeavours

- **Innovation system bottlenecks and 'frictions':** Challenges where there are a variety of innovation system barriers to connecting exploratory research efforts to different development, demonstration, and scale-up innovation activities
- **Mission challenges:** Challenges where a mission vision (and associated 'stretch goals') can bring a coherence to innovation efforts, and mandate to address any innovation bottlenecks

The Agency should follow the US ARPA model and not have its own labs or carry out its own research. It should be a *programme management* agency, where empowered programme managers develop portfolios of research projects, designed to catalyse technology development pathways, focused by a challenge-driven vision for the future of deployment and impact of the technology

- **What can be learned from ARPA equivalents in other countries?**

There are a range of ARPA equivalents in other countries, including the *Challenge-Driven Innovation* programme in Sweden and the *Strategic Innovation Programme* in Japan. One of the most interesting, however, is the US Department of Energy's *ARPA-E*, which has been the subject of a number of studies by academic scholars; as well as assessment by the National Academies [NASEM, 2017; Bonvillian, 2011, 2018; Azoulay, 2018]. These studies highlight, among other things:

- The challenges of commercialisation in a sector with incumbent technologies, legacy systems, and standards. And the variety of support needed across programmes areas where there are diverse established funding, commercialization, and deployment pathways.
- Unlike DARPA, ARPA-E projects does not benefit from a major (Department of Defense) follow-on procurement budget for system development, demonstration and scale-up. Instead, ARPA-E developed a '*Tech to Market*' programme for supporting its funded teams with industrialisation and commercialisation efforts
- Programme Managers with both academic and commercial sector experience (including venture capital) can be effective in identifying relevant scientific breakthroughs and anticipating potential commercialization pathways.
- Like DARPA, ARPA-E confers a 'halo effect' on those technologies which they have supported - giving a 'stamp of approval', based on the rigour of the selection process and esteem of PMs, which can attract subsequent private sector investment.

- **What benefits might be gained from basing UK ARPA outside of the 'Golden Triangle'?**

If the UK ARPA follows the US model and does not have its own research laboratories, but instead identifies and commissions the best research project teams *wherever they are to be found in the UK,* then the location of the UK ARPA headquarters itself is less critical. In this context, the most important consideration is about how the location might affect the agency's awareness, connectedness and understanding of the wider UK Research & Innovation system.

UK ARPA Programme Managers will need to have a deep understanding of relevant actors in the UK research system: where to find them, what their capabilities are, what facilities they possess, what opportunities they perceive, what innovation barriers they anticipate. Important insights and capabilities will be distributed across a range of actors: R&D-intensive firms, leading academic researchers, research & technology organisations, venture capital firms, other R&D agencies, etc.

Locating outside the 'Golden Triangle' might enhance awareness of innovative R&D teams outside the Golden Triangle 'bubble'. This would, however, need to be weighed against the potential that locating elsewhere may reduce connectedness within the region where key actors are most densely clustered.

References and recommended reading

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Reason for submitting evidence: Providing a technology management perspective on ARPA

My professional research agenda focuses on advancing our understanding of how new research knowledge gets translated into new technologies, industries and economic wealth. In particular, this research focuses on those complex R&D policy issues which require careful characterisation of different technologies, manufacturing systems, industrial structures.

My research projects are designed to have an impact on R&D agency practice, intended to generate an evidence base which can inform R&D agency officials design new R&D funding programmes, manage project portfolios, and develop emerging technology strategies.

Based on my analysis of ARPA / DARPA, I strongly believe that much of what makes the ARPA model effective is in the details of its technology management approach, when it in the technology lifecycle of an emerging technology it plays a role, and how it influences the configuration of technology innovation systems. This paper is intended, therefore, to contribute a technology management and innovation systems perspective on ARPA, which I believe will be essential to ensuring an effective design for the new UK research agency.

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