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## New meaning for *information gap*

The *Oxford English Dictionary* contains an entry for the phrase *information gap* in the entry “*information* with agent nouns”. The current *OED* entry reads: “*information gap* n. a deficiency or disparity in access to information.” I will document a new meaning for this phrase which appears extensively in published material in decision theory and its application in many fields. It is:

*Information gap* or *info-gap*: the disparity between what is known and what needs to be known in order to make a responsible plan, design or decision.

I will first present selected quotations which explicitly demonstrate early usage of information gap or info-gap in its new more focussed and technical meaning. These will be from my own work; I know of no earlier explicit usages with the new meaning. These will be followed by selected quotations from other authors illustrating the new usage. Finally, I will present many additional quotations.

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### 1 Earliest Examples of the New Usage

1. “Galbraith, in discussing the design of complex industrial organizations, defines uncertainty as an information gap, as ‘the difference between the amount of information required to perform the task and the amount of information already possessed by the organization.’<sup>1</sup>” Yakov Ben-Haim, 1996, *Robust Reliability in the Mechanical Sciences*, Springer-Verlag, (p.177).
2. “To use Galbraith’s expression, the uncertainty in this problem is a matter of the ‘information gap’ between what we know... and what we need to know ... in order to make a decision.” Yakov Ben-Haim, 1996, *Robust Reliability in the Mechanical Sciences*, Springer-Verlag, (p.180).
3. “The disparity between real and ideal shell is inevitable, but its magnitude is unknown, and this information gap between design and implementation is the starting point for robust reliability analysis. The central question is: how large an uncertainty in the shell shape can be tolerated?” Yakov Ben-Haim, 1996, *Robust Reliability in the Mechanical Sciences*, Springer-Verlag, (p.3).
4. “The gap between what the manufacturer *does know* ... and what *needs to be known* in order to implement the classical analysis ... is represented by an info-gap model.” Yakov Ben-Haim,

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<sup>1</sup>J. Galbraith, 1973, *Designing Complex Organizations*, Addison-Wesley Publ. Co., p.5.

2001, *Information-Gap Decision Theory: Decisions Under Severe Uncertainty*, 1st edition, Academic Press, London, (p.51).

5. “In employing an approximate model we are acknowledging a large information gap between what *is known* and what *needs to be known* in order to make fully competent decisions in the management of the toxic effluent.” Yakov Ben-Haim, 2001, *Information-Gap Decision Theory: Decisions Under Severe Uncertainty*, 1st edition, Academic Press, London, (p.14).

## 2 Selected Later Examples of the New Usage

1. “On the other hand, an information gap (info gap) model of robustness . . . appears prima facie to be well suited for environmental decision making under uncertainty.” Jason K. Levy, Keith W. Hipel and D. Marc Kilgour, 2000, Using environmental indicators to quantify the robustness of policy alternatives to uncertainty, *Ecological Modelling*, Vol. 130, Issue 1, pp.79–86. (p.81)
2. “This is the basis of information-gap (info-gap) decision theory, which seeks robust outcomes that are most immune to failure due to uncertainty (Ben-Haim 2001, 2004).” Emily Nicholson and Hugh P. Possingham, 2007, Conservation planning for the persistence of multiple species under uncertainty: an application of info-gap decision theory, *Ecological Applications*, 17: 251–265. (p.252)
3. “Rather than optimizing the expected outcome, the info-gap approach asks how wrong can one be and still get an acceptable result.” McCarthy, M.A., Lindenmayer, D.B., 2007, Info-gap decision theory for assessing the management of catchments for timber production and urban water supply, *Environmental Management*, 39 (4) pp. 553–562. (p.554)
4. “In structural engineering, the info-gap robustness function represents the greatest level of uncertainty at which any constraint on mechanical performance cannot be violated.” Matsuda, Y. and Y. Kanno, 2008, Robustness analysis of structures based on plastic limit analysis with uncertain loads, *Journal of Mechanics of Materials and Structures*, vol.3, pp.213–242. (p.214)
5. “An info-gap, in its simplest form, is the discrepancy between an uncertain quantity’s available (but suspect) nominal value and the quantity’s true value, which could be known but is not (Ben-Haim, 2006).” Duncan, S.J., Bras, B. and Paredis, C.J.J., 2008, An approach to robust decision making under severe uncertainty in life cycle design, *Int. J. Sustainable Design*, Vol. 1, No. 1, pp.45–59. (p.47)
6. “Thus, info-gaps characterise the difference between what is known and what needs to be known for the correct decision.” Thomas Knoke, 2008, Mixed forests and finance — Methodological approaches, *Ecological Economics*, Volume 65, Issue 3, pp.590–601. (p.594)

## 3 More Examples of the New Usage

1. “The use of info-gap models is motivated by the lack of sufficient data to reliably select a probabilistic model.” Yakov Ben-Haim, 1999, Design certification with information-gap uncertainty. *Structural Safety*. 21:269–289. (p.270)
2. “This probabilistic information can be combined with info-gap uncertainty models in various ways . . . .” Yakov Ben-Haim, 1999, Design certification with information-gap uncertainty. *Structural Safety*. 21:269–289. (p.282)
3. “Info-gap models quantify uncertainty as the size of the disparity between what *is known* and what *could be known*.” Yakov Ben-Haim, 1999, Design certification with information-gap uncertainty. *Structural Safety*. 21:269–289. (p.282) (p.287)

4. “[H]ow large an ‘information gap’ can we tolerate between the nominal and actual shapes of the shell?” Yakov Ben-Haim, 1997, Robust reliability of structures, *Advances in Applied Mechanics*, vol. 33, pp. 1–41.
5. “Unstructured uncertainty is a substantial *information-gap* between what we *do know* and what we *need to know* in order to perform optimally.” Yakov Ben-Haim and Alexander Laufer, 1998, Robust reliability of projects with activity-duration uncertainty, *ASCE Journal of Construction Engineering and Management*. 124: 125–132. (p.126)
6. “[t]he uncertainty parameter expresses the information gap between what is known . . . and what needs to be known for an ideal solution”. Yakov Ben-Haim and Alexander Laufer, 1998, Robust reliability of projects with activity-duration uncertainty, *ASCE Journal of Construction Engineering and Management*. 124: 125–132. (p.127)
7. “In employing an approximate model we are acknowledging a large *information gap* between what *is known* and what *needs to be known* in order to make rational decisions in the management of the toxic effluent.” Keith W. Hipel and Yakov Ben-Haim, 1999, Decision making in an uncertain world: Information-gap modelling in water resources management, *IEEE Trans., Systems, Man and Cybernetics*, Part C: Applications and Reviews, 29: 506–517. (p.509). (See also item 5 here.)
8. “Robust reliability is a new non-probabilistic theory of reliability of mechanical systems. It is based on information-gap models of uncertainty which express the gap between what is known and what needs to be known.” Yakov Ben-Haim, Ladislav Frýba and Nobuhiro Yoshikawa, Robust reliability of a dynamically loaded beam on an uncertain foundation. Computer Techniques for Civil and Structural Engineering, Oxford, 13–15 Sept. 1999. (p.1).
9. “The robust reliability of a system is defined as the amount of uncertainty (expressed as an info-gap) which is consistent with no-failure of the system.” Yakov Ben-Haim, Ladislav Frýba and Nobuhiro Yoshikawa, Robust reliability of a dynamically loaded beam on an uncertain foundation. Computer Techniques for Civil and Structural Engineering, Oxford, 13–15 Sept. 1999. (p.4)
10. “One must identify the information gap between what is known and what could be known. It is a highly speculative, subjective and tenuous task, but one must attempt to enhance the robustness of the mission to these uncertainties.” Yakov Ben-Haim, 1996, *Robust Reliability in the Mechanical Sciences*, Springer-Verlag, (p.218).
11. “Unanticipated deviations are the essence of info-gap uncertainty.” Yakov Ben-Haim, 2001, *Information-Gap Decision Theory: Decisions Under Severe Uncertainty*, 1st edition, Academic Press, London, (p.18).
12. “We find a simple expression for the info-gap solution, . . .” Rout, T.M., C.J.Thompson, and M.A.McCarthy, 2009, Robust decisions for declaring eradication of invasive species, *Journal of Applied Ecology*, vol. 46, pp.782–786, p.782.
13. “Because the parameters of the problem, such as the risk of fire and the effect of pines on water supply, are highly uncertain, we also analyze the problem using info-gap methods (Ben-Haim 2001).The info-gap approach to decision theory is particularly well suited to this decision problem because there is severe uncertainty that cannot be reliably described probabilistically within the time available for making the decision.” McCarthy, M.A., Lindenmayer, D.B., 2007, Info-gap decision theory for assessing the management of catchments for timber production and urban water supply, *Environmental Management*, 39 (4) pp. 553–562. (p.555).

14. “Rather than trying to maximize the expected value, the info-gap approach determines robust management options that guarantee a minimally satisfactory level of performance EVc.” McCarthy, M.A., Lindenmayer, D.B., 2007, Info-gap decision theory for assessing the management of catchments for timber production and urban water supply, *Environmental Management*, 39 (4) pp. 553–562. (p.557)
15. “Info-gap methods differ from other non/probabilistic approaches to decision theory such as min-max (Winkler 1972) and pareto optimisation (Cohon 1978) in several ways (Ben-Haim 2001; Halpern and others 2006).” McCarthy, M.A., Lindenmayer, D.B., 2007, Info-gap decision theory for assessing the management of catchments for timber production and urban water supply, *Environmental Management*, 39 (4) pp. 553–562. (p.559)
16. “Although info-gap methods and min-max approaches use the mathematical operators minimum and maximum, they have fundamentally different mathematical structures.” McCarthy, M.A., Lindenmayer, D.B., 2007, Info-gap decision theory for assessing the management of catchments for timber production and urban water supply, *Environmental Management*, 39 (4) pp. 553–562. (p.559)
17. “An information-gap approach seeks robust outcomes that are most immune from error.” Emily Nicholson and Hugh P. Possingham, 2007, Conservation planning for the persistence of multiple species under uncertainty: an application of info-gap decision theory, *Ecological Applications*, 17: 251–265. (p.251)
18. “A novel component of info-gap theory is that uncertainty is unknown and unbounded, rather than assuming probability distributions or ranges for model parameters, making it particularly useful where information is scarce.” Emily Nicholson and Hugh P. Possingham, 2007, Conservation planning for the persistence of multiple species under uncertainty: an application of info-gap decision theory, *Ecological Applications*, 17: 251–265. (p.255)
19. “The difference between our best estimate and the ‘true’ value is the information gap, or info-gap (Ben-Haim 2004).” Emily Nicholson and Hugh P. Possingham, 2007, Conservation planning for the persistence of multiple species under uncertainty: an application of info-gap decision theory, *Ecological Applications*, 17: 251–265. (p.256)
20. “The most robust scenario allows the greatest info-gap between our best estimate and the true value, while guaranteeing the specified performance.” Emily Nicholson and Hugh P. Possingham, 2007, Conservation planning for the persistence of multiple species under uncertainty: an application of info-gap decision theory, *Ecological Applications*, 17: 251–265. (p.256)
21. “Info-gap is especially suitable when probabilistic models of uncertainty are unreliable, inappropriate or unavailable (Regan et al. 2005).” L. R. Carrasco, R. Baker, A. MacLeod, J. D. Knight, and J. D. Mumford Optimal and robust control of invasive alien species spreading in homogeneous landscapes *J. R. Soc. Interface*, March 6, 2010 7:529–540, see p.4; Copy in \letters\carrasco-roman01.pdf
22. “The essence of info-gap analysis is the pursuit of decisions that are robust in the sense that they maximize the range of uncertainty about model parameters within which the decision maker is certain to achieve a specified performance criterion.” L. Joe Moffitt, John K. Stranlund and Craig D. Osteen, 2008, Robust detection protocols for uncertain introductions of invasive species, *Journal of Environmental Management*, vol.89, pp.293–299, see p.294. Copy in \website\IGT\moffitt-et-al2008.pdf.
23. “Info-gap decision theory is designed for decisions in which probability distributions for uncontrolled events are not available. The essence of info-gap is pursuit of a performance requirement over the largest possible “range” of uncontrolled events. . . . (Ben-Haim, 2001).” L. Joe Moffitt,

- John K. Stranlund, and Barry C. Field, 2005, Inspections to Avert Terrorism: Robustness Under Severe Uncertainty, *Journal of Homeland Security and Emergency Management*, Vol. 2: No. 3. (p.2)
24. “Unlike other common forms of uncertainty analysis, the info-gap uncertainty model does not require a specific probability distribution or plausible interval for uncertain parameters (Ben-Haim 2006).” Rout, T.M., C.J.Thompson, and M.A.McCarthy, 2009, Robust decisions for declaring eradication of invasive species, *Journal of Applied Ecology*, vol. 46, pp.782–786, p.783.
  25. “For ecological management in the face of uncertainty, managers may use info-gap to gain some protection against catastrophic outcomes by answering the question: how wrong could this model be before outcomes are unacceptably bad?” Rout, T.M., C.J.Thompson, and M.A.McCarthy, 2009, Robust decisions for declaring eradication of invasive species, *Journal of Applied Ecology*, vol. 46, pp.782–786, p.785.
  26. “An info-gap analysis is fundamentally different from a sensitivity analysis as it finds the decision that enables maximum uncertainty while still meeting a minimum performance requirement.” Rout, T.M., C.J.Thompson, and M.A.McCarthy, 2009, Robust decisions for declaring eradication of invasive species, *Journal of Applied Ecology*, vol. 46, pp.782–786, p.786.
  27. “Because the information-gap theory considers future uncertainty that is not reflected in historical data, it is well suited to supplement the information which we can obtain by the classical approaches.” Thomas Knoke, 2008, Mixed forests and finance — Methodological approaches, *Ecological Economics*, Volume 65, Issue 3, pp.590–601. (p.599)
  28. “We thus conclude that considering info-gaps on variance estimation could certainly improve robust decisionmaking under severe uncertainty.” Patrick Hildebrandt and Thomas Knoke, 2009, Optimizing the shares of native tree species in forest plantations with biased financial parameters, *Ecological Economics*, vol.68, issue 11, pp. 2825–2833. (p.2831)
  29. “It describes the information-gap that results from the difference between what we know and what is needed to draw a correct decision.” Patrick Hildebrandt and Thomas Knoke, 2009, Optimizing the shares of native tree species in forest plantations with biased financial parameters, *Ecological Economics*, vol.68, issue 11, pp. 2825–2833. (p.2827)
  30. “Using info-gap, we are not trying to find the strategy that maximizes the expected number of extant subpopulations but determine a robust management strategy that guarantees a minimally satisfactory level of performance, Ec.” Eve McDonald-Madden, Peter W. J. Baxter and Hugh P. Possingham, 2008, Making robust decisions for conservation with restricted money and knowledge, *Journal of Applied Ecology*, 45, pp.1630–1638. (p.1633)
  31. “Information-gap theory can accommodate nonstatistical uncertainties such as the subjective choice of candidate variables and the structural assumptions embedded in spatial analysis.” Moilanen, A., B.A. Wintle., J. Elith and M. Burgman, 2006, Uncertainty analysis for regional-scale reserve selection. *Conservation Biology*, Vol.20, No. 6, 1688–1697. (p.1695)
  32. “Info-gap decision theory (Ben-Haim, 2001) was developed for decisions in the face of severe uncertainty.” Moilanen, A. and B.A. Wintle, 2006, Uncertainty analysis favours selection of spatially aggregated reserve structures. *Biological Conservation*, Volume 129, Issue 3, May 2006, Pages 427–434. (p.428)
  33. “Following the conventions of Info-Gap Theory (Ben-Haim [2]) we quantify the amount of epistemic uncertainty (ignorance) with a parameter called  $\alpha$ .” D. Berleant, L. Andrieu, J.-P. Argaud, F. Barjon, M.-P. Cheong, M. Dancre, G. Sheble and C.-C. Teoh, 2008, Portfolio management under epistemic uncertainty using stochastic dominance and information-gap theory, *International Journal of Approximate Reasoning*, vol.49, issue #1, pp.101–116. (p.110)

34. “The uncertainty is represented by an info-gap model.” Kazem Zare, Antonio J. Conejo, Miguel Carrion, and Mohsen Parsa Moghaddam, 2010, Multi-market energy procurement for a large consumer using a risk-aversion procedure, *Electric Power Systems Research*, vol.80, pp.63–70. (p.69)
35. “The uncertainty can be modeled by an info-gap model.” Kazem Zare, Mohsen Parsa Moghaddam and Mohammad Kazem Sheikh El Eslami, 2010, Demand bidding construction for a large consumer through a hybrid IGDT-probability methodology, *Energy*, vol.35, pp.2999-3007, (p.3007)
36. “The uncertainty can be modeled using an info-gap model.” Kazem Zare, Mohsen Parsa Moghaddam, and Mohammad Kazem Sheikh El Eslami, 2010, Electricity procurement for large consumers based on Information Gap Decision Theory, *Energy Policy*, vol. 38, pp.234–242, (p.237)
37. “Info-gap model: When the level of uncertainty is unknown, only a family of uncertainty sets, rather than a unique set, can be specified.” Zacksenhouse, M., R. Bogacz and P. Holmes, 2010, Robust versus optimal strategies for two-alternative forced choice tasks, *Journal of Mathematical Psychology*, vol. 54, pp.230–246 (p.236)
38. “Such a structure is known as an information-gap (info-gap) model of uncertainty (Ben-Haim, 2006).” Zacksenhouse, M., R. Bogacz and P. Holmes, 2010, Robust versus optimal strategies for two-alternative forced choice tasks, *Journal of Mathematical Psychology*, vol. 54, pp.230–246 (p.237)
39. “. . . we describe the uncertainty in the observations by an information-gap (info-gap) model” Miriam Zacksenhouse, Simona Nemets, Miikhail A Lebedev and Miguel A Nicolelis, 2009, Robust Satisficing Linear Regression: performance/robustness trade-off and consistency criterion, *Mechanical Systems and Signal Processing*, vol. 23, pp.1954–1964 (p.1955)
40. “Such a structure is referred to as an info-gap (short for information-gap) model of uncertainty [10].” Miriam Zacksenhouse, Simona Nemets, Miikhail A Lebedev and Miguel A Nicolelis, 2009, Robust Satisficing Linear Regression: performance/robustness trade-off and consistency criterion, *Mechanical Systems and Signal Processing*, vol. 23, pp.1954–1964 (p.1956)
41. “We developed an info-gap robust satisficing approach to regression” Miriam Zacksenhouse, Simona Nemets, Miikhail A Lebedev and Miguel A Nicolelis, 2009, Robust Satisficing Linear Regression: performance/robustness trade-off and consistency criterion, *Mechanical Systems and Signal Processing*, vol. 23, pp.1954–1964 (p.1962)
42. “The info-gap approach emphasizes the trade-off between performance and robustness” Miriam Zacksenhouse, Simona Nemets, Miikhail A Lebedev and Miguel A Nicolelis, 2009, Robust Satisficing Linear Regression: performance/robustness trade-off and consistency criterion, *Mechanical Systems and Signal Processing*, vol. 23, pp.1954–1964 (p.1962)
43. “We model uncertainty of an actor’s energy and location as an information-gap,” Chinnappen-Rimer, S. and Hancke, G.P., 2009, Actor coordination in wireless sensor-actor networks, IEEE India Council Conference, INDICON 2009; Ahmedabad; 18-20 December 2009. (p.1)
44. “This paper explores the use of information gap theory to analyze the sensitivity of flood management decisions to uncertainties in flood inundation models and flood frequency analysis. Information gap is a quantified nonprobabilistic theory of robustness.” Hine, Daniel and Jim W. Hall, 2010, Information gap analysis of flood model uncertainties and regional frequency analysis, *Water Resources Research*, vol. 46, (p.1)

45. “This technique is based on the theory of convex models and information-gap uncertainty as pioneered by Ben-Haim and co-workers [17–20].” S.G. Pierce, K. Worden and G. Manson, 2006, A novel information-gap technique to assess reliability of neural network-based damage detection *Journal of Sound and Vibration*, vol. 293, Issues 1–2, pp.96–111. (p.97)
46. “One means of identifying robust designs is information-gap decision theory (IGDT), developed by Ben-Haim [2].” Duncan, S.J., Paredis, C.J.J., Bras, B., 2008, Applying info-gap theory to re-manufacturing process selection affected by severe uncertainty, ASME International Mechanical Engineering Congress and Exposition, Proceedings Vol. 15, pp.293–300. (p.294)
47. “In other words, info-gap robustness is the greatest amount of error in the nominal that a design can endure and still perform well (but not necessarily optimally).” Duncan, S.J., Bras, B. and Paredis, C.J.J., 2008, An approach to robust decision making under severe uncertainty in life cycle design, *Int. J. Sustainable Design*, Vol. 1, No. 1, pp.45–59. (p.48)
48. “Info-gap models are meant for use when much less information is available than is required by other uncertainty representations.” Duncan, S.J., Bras, B. and Paredis, C.J.J., 2008, An approach to robust decision making under severe uncertainty in life cycle design, *Int. J. Sustainable Design*, Vol. 1, No. 1, pp.45–59. (p.55)
49. “Info-gap models quantify uncertainties as the size of the gap between what is known (nominal values of parameters  $\tilde{u}_i$ ) and what could be known (size of the domain of uncertainty).” P. Vinot, S. Cogan and V. Cipolla, 2005, A robust model-based test planning procedure, *Journal of Sound and Vibration*, Volume 288, Issue 3, pp.571–585. (p.574)
50. “Various uncertainties are considered for the live, dead, and reference disturbance loads based on the nonstochastic info-gap uncertainty model.” Matsuda, Y. and Y. Kanno, 2008, Robustness analysis of structures based on plastic limit analysis with uncertain loads, *Journal of Mechanics of Materials and Structures*, vol.3, pp.213–242. (p.213)
51. “Recently, the info-gap decision theory has been proposed as a nonprobabilistic decision theory under uncertainties [Ben-Haim 2006], and has been applied to wide fields.” Matsuda, Y. and Y. Kanno, 2008, Robustness analysis of structures based on plastic limit analysis with uncertain loads, *Journal of Mechanics of Materials and Structures*, vol.3, pp.213–242. (p.214)
52. “The magnitude of uncertainty is unknown and cannot be characterized by a statistical distribution. Info-gap theory (Ben-Haim 2001) can be used in these circumstances, . . .” Terry Walshe and Tilo Massenbauer, 2008, Decision-making under climatic uncertainty: A case study involving an Australian Ramsar-listed wetland, *Ecological Management and Restoration*, Volume 9, Issue 3, December 2008, Pages 202–208, (p.205)