

FUNDAMENTAL SOLUTIONS: A BRIEF REVIEW

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Abstract. We review briefly the fundamental solutions to some of the most important partial differential operators. These are very crucial in analysis and partial differential equations (PDEs). Among several applications, these are used, for instance, in studying regularity and growth of solutions.

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REFERENCES

- [1] L. AMBROSIO, H. M. SONER, *Level set approach to mean curvature flow in arbitrary codimension*, Journal of Differential Geometry, **43**, (1996), 693–737.
- [2] S. N. ARMSTRONG, C. K. SMART, B. SIRAKOV, *Fundamental solutions of homogeneous fully nonlinear elliptic equations*, Communications on Pure and Applied Mathematics, **64**, 6 (2011), 737–777.
- [3] S. N. ARMSTRONG, M. TROKHIMTCHOUK, *Long-time asymptotics for fully nonlinear homogeneous parabolic equations*, Calculus of Variations and Partial Differential Equations, **38**, (2010), 521–540.
- [4] J. BARROS-NETO, F. CARDOSO, *Gellerstedt and Laplace-Beltrami operators relative to a mixed signature metric*, Annali di Matematica Pura ed Applicata, **188**, (2009), 497–515.
- [5] J. BARROS-NETO, F. CARDOSO, *Hypergeometric functions and the Tricomi operator*, Advances in Differential Equations, **10**, 4 (2005), 445–461.
- [6] J. BARROS-NETO, F. CARDOSO, *Hypergeometric functions and the Tricomi operators: pole in the elliptic region*, Selecta Mathematica, New Series, **11**, (2005), 309–324.
- [7] J. Barros-Neto, I. M. Gelfand, *Fundamental solutions for the Tricomi operator*, Duke Mathematical Journal, **98**, 3 (1999), 465–483.
- [8] J. BARROS-NETO, I. M. GELFAND, *Fundamental solutions for the Tricomi operator II*, Duke Mathematical Journal, **111**, 3 (2002), 561–584.
- [9] J. BARROS-NETO, I. M. GELFAND, *Fundamental solutions for the Tricomi operator III*, Duke Mathematical Journal, **128**, 1 (2005), 119–140.
- [10] A. BENSOUSSAN, J. L. LIONS, *Applications of variational inequalities in stochastic control*, Translated from the French, Studies in Mathematics and its Applications, **12**, North-Holland Publishing Co., Amsterdam-New York, 1982.
- [11] T. BIESKE, J. GONG, *The P -Laplace equation on a class of Grushin-type spaces*, Proceedings of the American Mathematical Society, **134**, 12 (2006), 3585–3594.
- [12] I. BIRINDELLI, G. GALISE, E. TOPP, *Fractional truncated Laplacians: representation formula, fundamental solutions and applications*, Nonlinear Differential Equations and Applications NoDEA, **29**, (2022), Article number: 26.
- [13] C. BUCUR, *Some observations on the Green function for the ball in the fractional Laplace framework*, Communications on Pure and Applied Analysis, **15**, 2 (2016), 657–699.
- [14] L. CAFFARELLI, A. VASSEUR, *Drift diffusion equations with fractional diffusion and the quasi-geostrophic equation*, Annals of Mathematics, **171**, 3 (2010), 1903–1930.

- [15] L. CAFFARELLI, L. SILVESTRE, *Regularity theory for fully nonlinear integro-differential equations*, Communications on Pure and Applied Mathematics, **62**, (2009), 597–638.
- [16] L. CAPOGNA, D. DANIELI, N. GAROFALO, *Capacity estimates and the local behaviour of solutions of nonlinear subelliptic equations*, American Journal of Mathematics, **118**, 6 (1996), 1153–1196.
- [17] Y. CHEN, S. LEVINE, M. RAO, *Variable exponent, linear growth functionals in image restoration*, SIAM Journal on Applied Mathematics, **66**, 4 (2006), 1383–1406.
- [18] F. CÎRSTEĂ, *A complete classification of the isolated singularities for nonlinear elliptic equations with inverse square potentials*, Memoirs of the American Mathematical Society, **227**, 1068 (2014), 1–97.
- [19] A. CÓRDOBA, D. CÓRDOBA, *A maximum principle applied to quasi-geostrophic equations*, Communications in Mathematical Physics, **249**, 3 (2004), 511–528.
- [20] M. G. CRANDALL, L. C. EVANS, R. F. GARIEPY, *Optimal Lipschitz extensions and the infinity Laplacian*, Calculus of Variations and Partial Differential Equations, **13**, 2 (2001), 123–139.
- [21] A. CUTRÍ, F. LEONI, *On the Liouville property for fully nonlinear equations*, Annales de l’Institut Henri Poincaré C, Analyse Non Linéaire, **17**, 2 (2000), 219–245.
- [22] A. CUTRÍ, N. TCHOU, *Barrier functions for Pucci-Heisenberg operators and applications*, International Journal of Dynamical Systems and Differential Equations, **1**, 2 (2008), 117–131.
- [23] S. DELACHE, J. LERAY, *Calcul de la solution élémentaire de l’opérateur d’Euler-Poisson-Darboux et de l’opérateur de Tricomi-Clairaut, hyperbolique d’ordre 2*, Bulletin de la Société Mathématique de France, **99**, (1971), 313–336.
- [24] S. DIPIERRO, E. VALDINOCI, *Elliptic partial differential equations from an elementary viewpoint*, Preprint, arXiv:2101.07941.
- [25] L. EHRENPREIS, *Solution of some problems of division. Part I. Division by a polynomial of derivation*, American Journal of Mathematics, **76**, (1954), 883–903.
- [26] T. G. ERGASHEV, *Fundamental Solutions for a class of multidimensional elliptic equations with several singular coefficients*, Journal of Siberian Federal University. Mathematics and Physics, **13**, 1 (2020), 48–57.
- [27] T. G. ERGASHEV, *On fundamental solutions for multidimensional Helmholtz equation with three singular coefficients*, Computer and Mathematics with Applications, **77**, (2019), 69–76.
- [28] L. C. EVANS, *Partial differential equations*, Graduate Studies in Mathematics, **19**, American Mathematical Society, Providence, RI, 1998.
- [29] P. L. FELMER, A. QUAAS, *Fundamental solutions and two properties of elliptic maximal and minimal operators*, Transactions of the American Mathematical Society, **361**, 11 (2009), 5721–5736.
- [30] P. L. FELMER, A. QUAAS, *Fundamental solutions and Liouville type theorems for nonlinear integral operators*, Advances in Mathematics, **226**, (2011), 2712–2738.
- [31] P. FELMER, A. QUAAS, *On Critical exponents for the Pucci’s extremal operators*, Annales de l’Institut Henri Poincaré C, Analyse Non Linéaire, **20**, 5 (2003), 843–865.
- [32] R. FEYNMAN, R. LEIGHTON, M. SANDS, *The Feynman Lectures in Physics*, **II**, Addison-Wesley, 1966.
- [33] G. B. FOLLAND, *Fundamental solution for a subelliptic operator*, Bulletin of the American Mathematical Society, **79**, (1973), 373–376.
- [34] F. FRANKL, *On the problems of Chaplygin for mixed sub and supersonic flows*, Bulletin de l’Académie des Sciences de L’URSS, **9**, (1945), 121–143.
- [35] I. B. GARIPOV, R. M. MAVLYAVIEV, *Fundamental solution of multidimensional axisymmetric Helmholtz equation*, Complex variables and elliptic equations, **62**, (2017), 287–296.
- [36] I. B. GARIPOV, R. MAVLYAVIEV, *Fundamental solution of two multi-dimensional elliptic equation*, Electronic Journal of Differential Equations, **2018**, 100 (2018), 1–12.
- [37] N. GAROFALO, *Fractional thoughts*, Preprint, arXiv:1712.03347.
- [38] S. GELLERSTEDT, *Sur une équation linéaire aux dérivées partielles de type mixte*, Arkiv för Matematik, Astronomi och Fysik, **25A**, 29 (1937).
- [39] S. GELLERSTEDT, *Sur un problème aux limites pour l’équation $y^{2s}z_{xx} + z_{yy} = 0$* , Arkiv för Matematik, Astronomi och Fysik, **25A**, 10 (1935).
- [40] V. V. GRUSHIN, *On a class of hypoelliptic operators*, Mathematics of the USSR-Sbornik, **12**, 3 (1970), 458–476.
- [41] B. GUERCH, L. VÉRON, *Local properties of stationary solutions of some nonlinear singular Schrödinger equations*, Revista Matemática Iberoamericana **7**, 1 (1991), 65–114.

- [42] A. HASANOV, E. T. KARIMOV, *Fundamental solutions for a class of three-dimensional elliptic equations with singular coefficients*, Applied Mathematics Letters, **22**, 12 (2009), 1828–1832.
- [43] A. HASANOV, R. B. SEILKHANOVA, *Particular solutions of generalized Euler-Poisson-Darboux equation*, Electronic Journal of Differential Equations, **2015**, 9 (2015), 1–10.
- [44] A. HASANOV, A. S. BERDYSHEV, A. R. RYKSAN, *Fundamental solutions for a class of four-dimensional degenerate elliptic equation*, Complex Variables and Elliptic Equations, **65**, 4 (2020), 632–647.
- [45] N. V. KRYLOV, *Boundedly nonhomogeneous elliptic and parabolic equations*, Izvestiya Akademii Nauk SSSR, Seriya Matematicheskaya, **46**, 3 (1982), 487–523.
- [46] N. V. KRYLOV, *Boundedly nonhomogeneous elliptic and parabolic equations in a domain*, Izvestiya Akademii Nauk SSSR, Seriya Matematicheskaya, **47**, 1 (1983), 75–108.
- [47] D. A. LABUTIN, *Isolated singularities for fully nonlinear elliptic equations*, Journal of Differential Equations, **177**, 1 (2001), 49–76.
- [48] P. LINDQVIST, *Notes on the Infinity Laplace Equation*, Springer Briefs in Mathematics, Springer Cham, 2016.
- [49] B. MALGRANGE, *Existence et approximation des solutions des équations aux dérivées partielles et des équations de convolution*, Annales de l’institut Fourier **6**, (1955/56), 271–355.
- [50] N. ORTNER, P. WAGNER, *Fundamental Solutions of Linear Partial Differential Operators*, Springer, Cham, 2015.
- [51] G. P. OVANDO, M. SUBLIS, *Magnetic trajectories on 2-step nilmanifolds*, The Journal of Geometric Analysis, **33**, (2023), Article number: 186.
- [52] L. SCHWARTZ, *Théorie des distributions*, Nouv. éd., Hermann, Paris, 1966.
- [53] F. TRICOMI, *Sulle equazioni lineari alle derivate parziali di secondo ordine di tipo misto*, Rendiconti Lincei. Scienze Fisiche Matematiche Naturali, **14**, (1923), 134–247.
- [54] J. L. VÁZQUEZ, *Asymptotic behaviour methods for the heat equation*, Convergence to the Gaussian, preprint, arXiv:1706.10034.
- [55] J. L. VÁZQUEZ, *The evolution fractional p -Laplacian equation in \mathbb{R}^N , Fundamental solution and asymptotic behaviour*, Nonlinear Analysis, **199**, (2020), Article number: 112034.
- [56] H. WEYL, *The theory of groups and quantum mechanics*, Dover Publications, New York, 1950.
- [57] K. YAGDJIAN, *A note on the fundamental solution for the Tricomi-type equation in the hyperbolic domain*, Journal of Differential Equations, **206**, (2004), 227–252.